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Direct Detection of CDM: The challenge ahead

- Non-baryonic Galactic Dark Matter close to a paradigm (certainly in the mind of many) but yet to be detected.

- ~20-30% Cold (non-relativistic) DM presently favored (we don't seem to be able to explain large scale structure of the universe without WIMPs –Weakly Interacting Massive particles-, relics of early stages)

- Cautious strategy: start by looking first for non-ad hoc particle candidates, i.e., those already invoked by particle theories (E.g., neutralino ↔ MSSM, axions ↔ strong CP problem)

- WIMPs: dominant interaction via low-energy nuclear elastic scattering, expected rates << 1 kg target / day in the keV region. (local ρ~0.4 GeV/cm^3, $<v>$~300 km/s, $\sigma<10^{-42}$ cm^2). Supersymmetric WIMPS can have rates as low as 1 recoil/tonne/yr!

- The challenge: build cost-effective tonne or multi-tonne detectors sensitive exclusively to WIMP-induced nuclear recoils (down to 1/year) and nothing else. Not even neutron recoils. Nada. Zilch.

- The scale of things: a 1-kg Ge detector fires in this room at the tune of ~1 kHz (OK to giggle at this point).

WIMP searches: a quixotic fight against backgrounds

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Particle dark matter? The number of candidates is comparable to the ~30 experiments to detect it.

- Standard model neutrinos
- Sterile neutrinos
- **Axions**
- **Supersymmetric dark matter** (**neutralinos**, sneutrinos, gravitinos, axinos)
- Light scalar dark matter
- Little Higgs dark matter
- Kaluza-Klein dark matter
- Superheavy dark matter (simpzillas)
- Q-balls
- CHArged massive particles (CHAMPS)
- Self-interacting dark matter
- D-matter
- Cryptons
- Superweakly interacting dark matter (SWIMPS)
- Brane-world dark matter
- Heavy 4^{th} generation neutrinos
- Mirror particles
- Etc. etc.

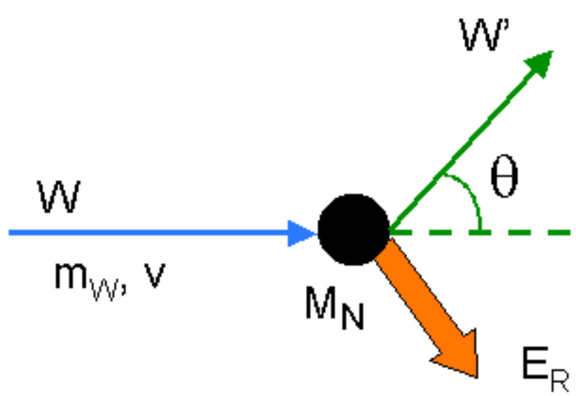
Patient compilation by C. Hailey (Columbia)

Do we know anything about these particles?

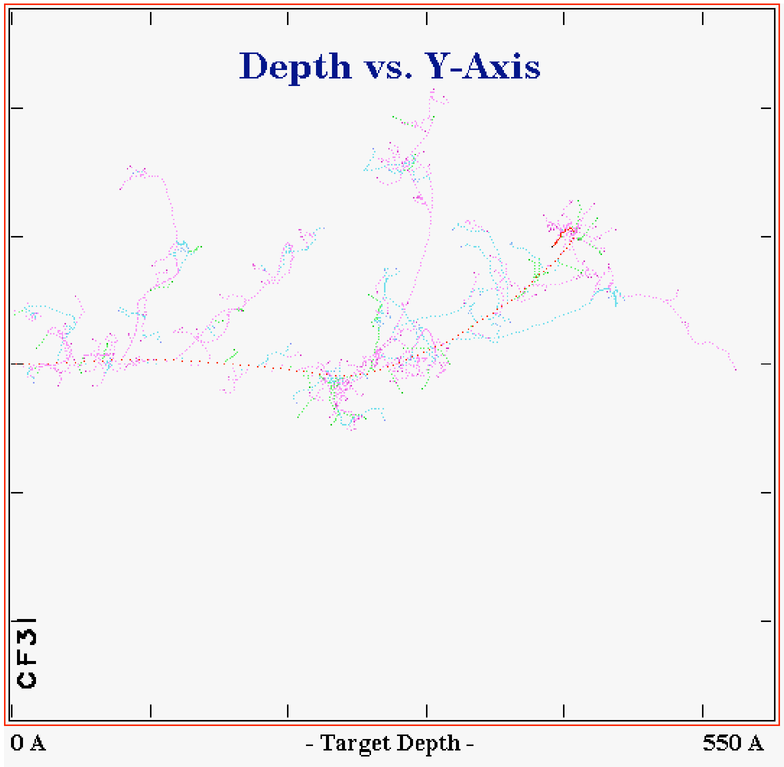
- Some are expected in particle theories having nothing to do with the dark matter problem.
(E.g., neutralino ↔ supersymmetry, axions ↔ strong CP problem)

- Supersymmetry attempts to find a common explanation to all known forces in nature. It predicts the existence of new stable particles with the right mass range and stability to make up the galactic dark matter.

- We expect these to interact (very rarely!) with known matter via "nuclear recoils" = billiard ball collisions. Known particles (e.g. neutrons) can produce the same.



(click on frame to run movie)



Things that go bump in the night.

Few keV iodine recoils injected into CF3I. Movie available from http://cfcp.uchicago.edu/~collar/IonCF3I_1.mov

WIMP Phenomenology: a way to avoid embarrassment (or is it?)

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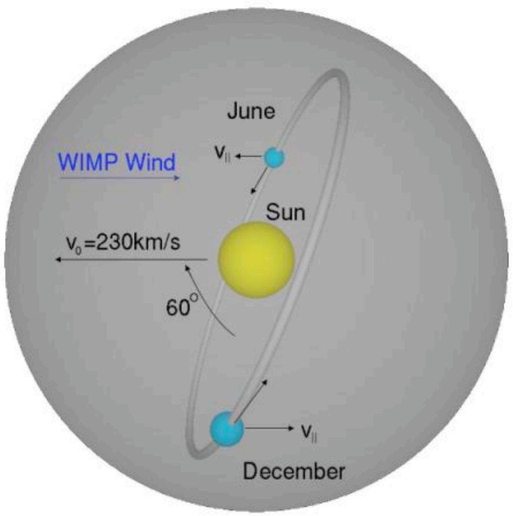
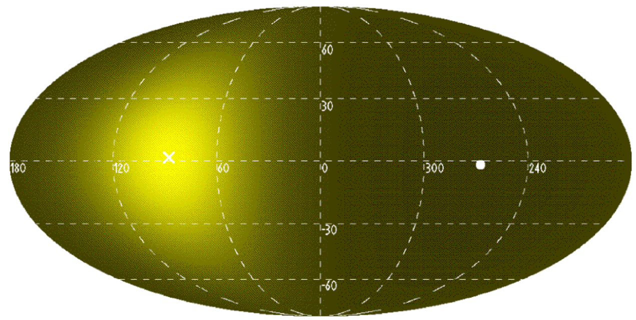
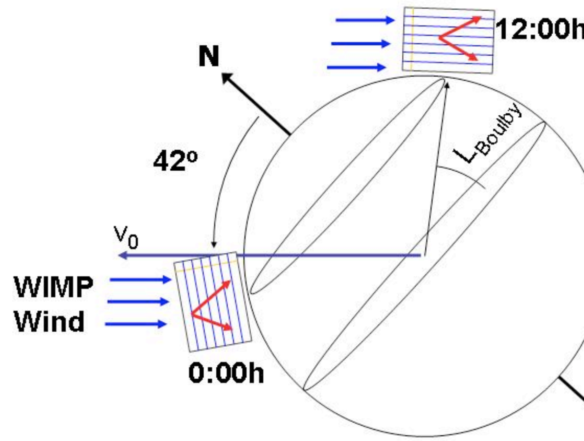
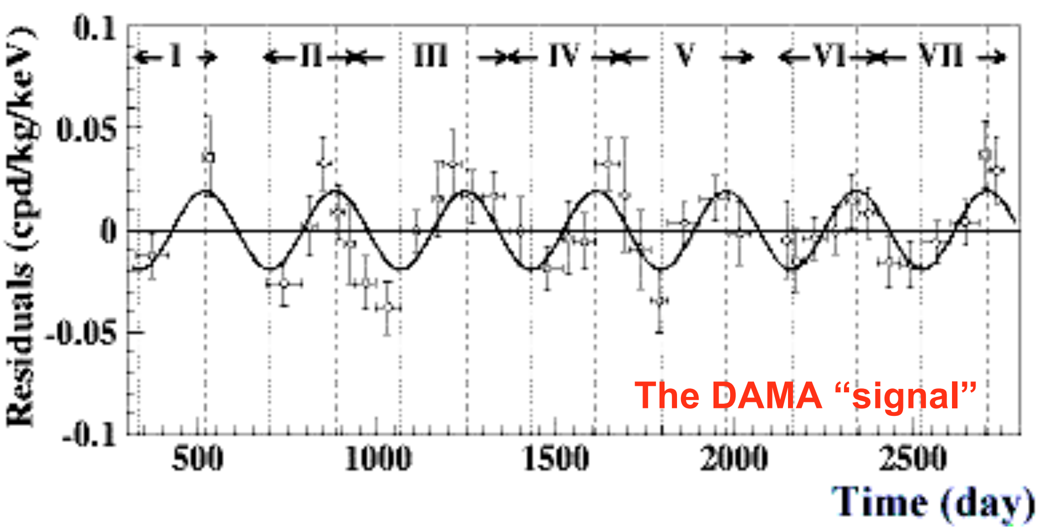
A “WIMP wind” from Cygnus

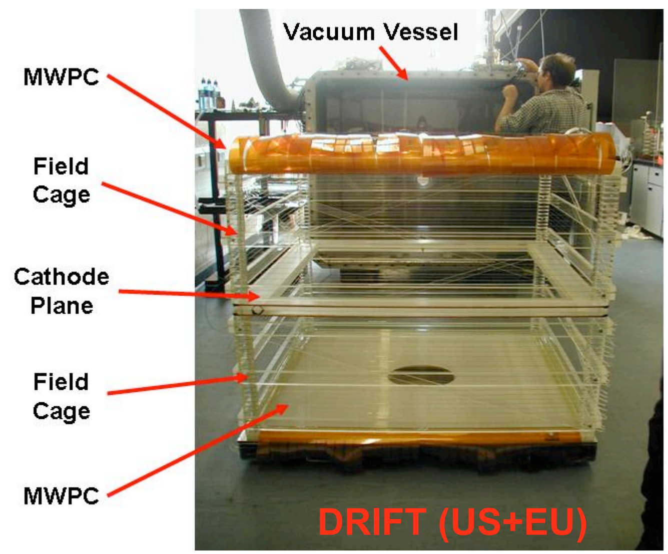






Directional detectors, a dream come true

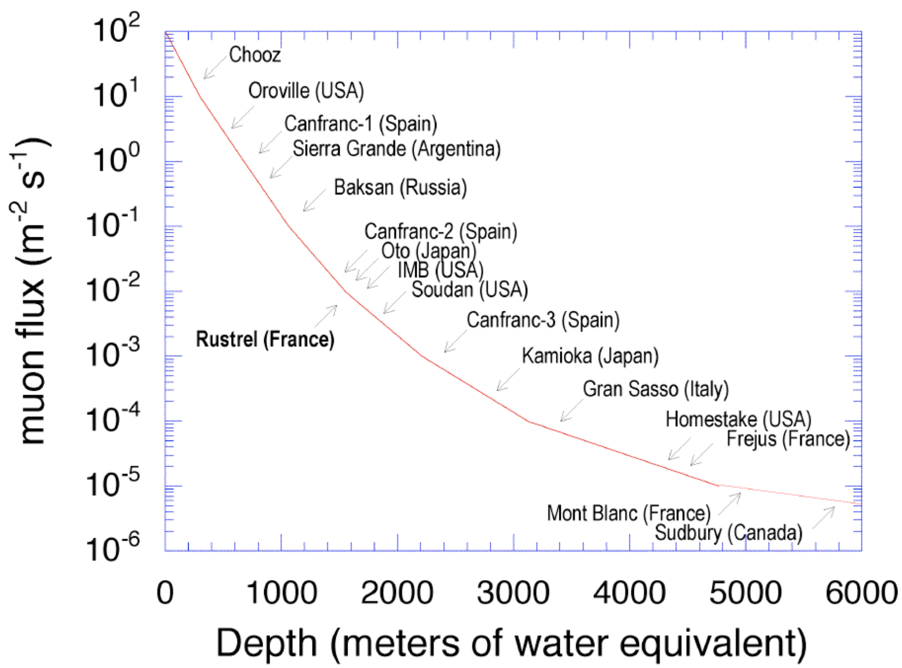




From ~1000/kg/s to ~1/ton/year
(you have to be kidding me)

- Deep bag of tricks: radiation shielding, radiopurity of materials (careful selection), underground sites, and background rejection.

Cozy (1 mile underground)



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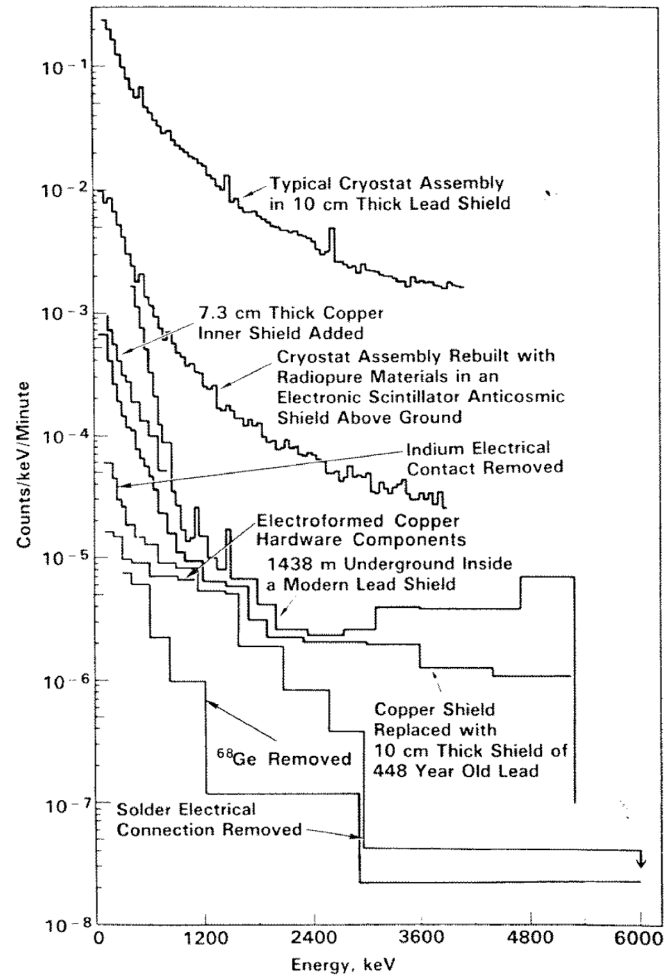
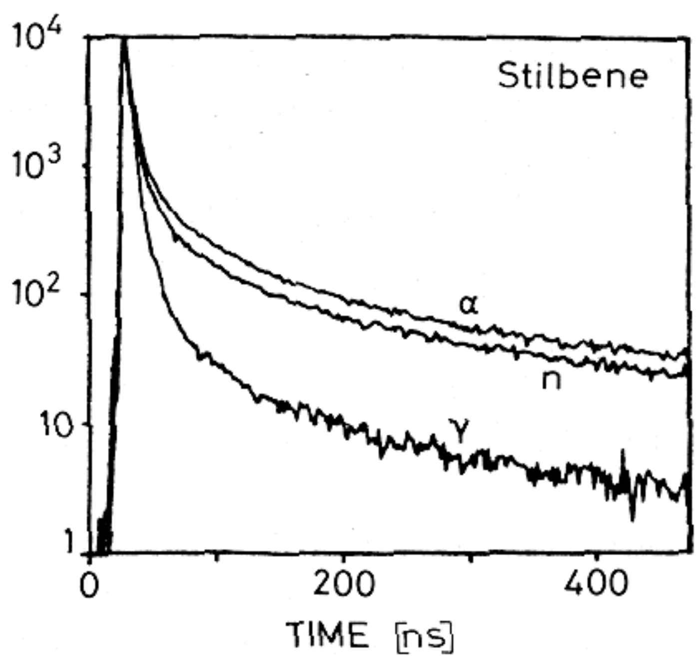
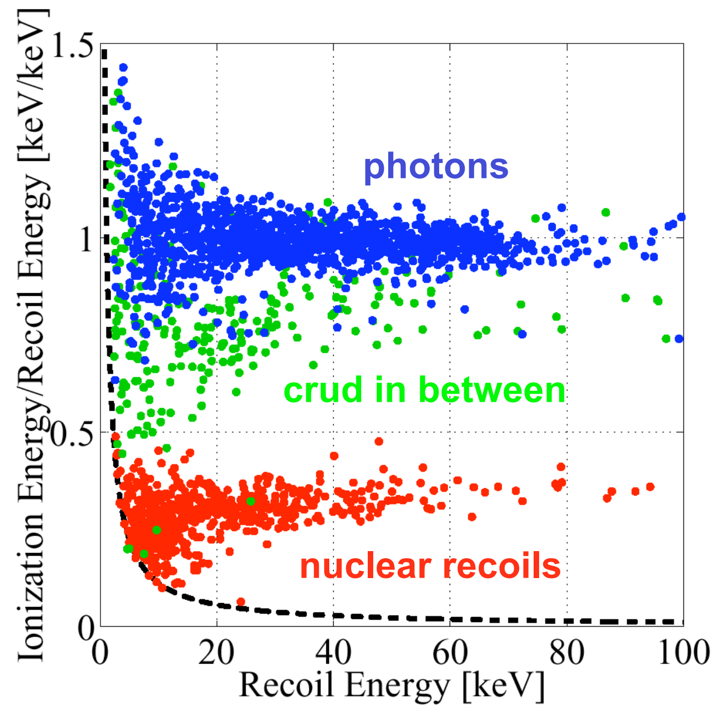


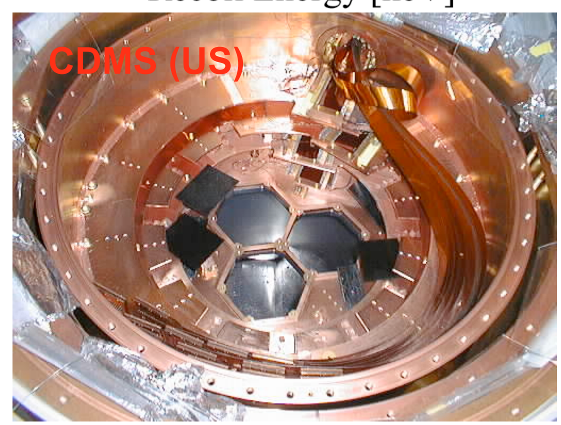
Fig. 1. Improvements in low-background technology.

From ~1000/kg/s to ~1/ton/year
(you have to be kidding me)

- Deep bag of tricks: radiation shielding, radiopurity of materials (careful selection), underground sites, and background rejection.







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Parental advisory:

What follows is not an unbiased review

Give to Cesar what belongs to Cesar...
Let us start with CDMS

Inside the icebox,

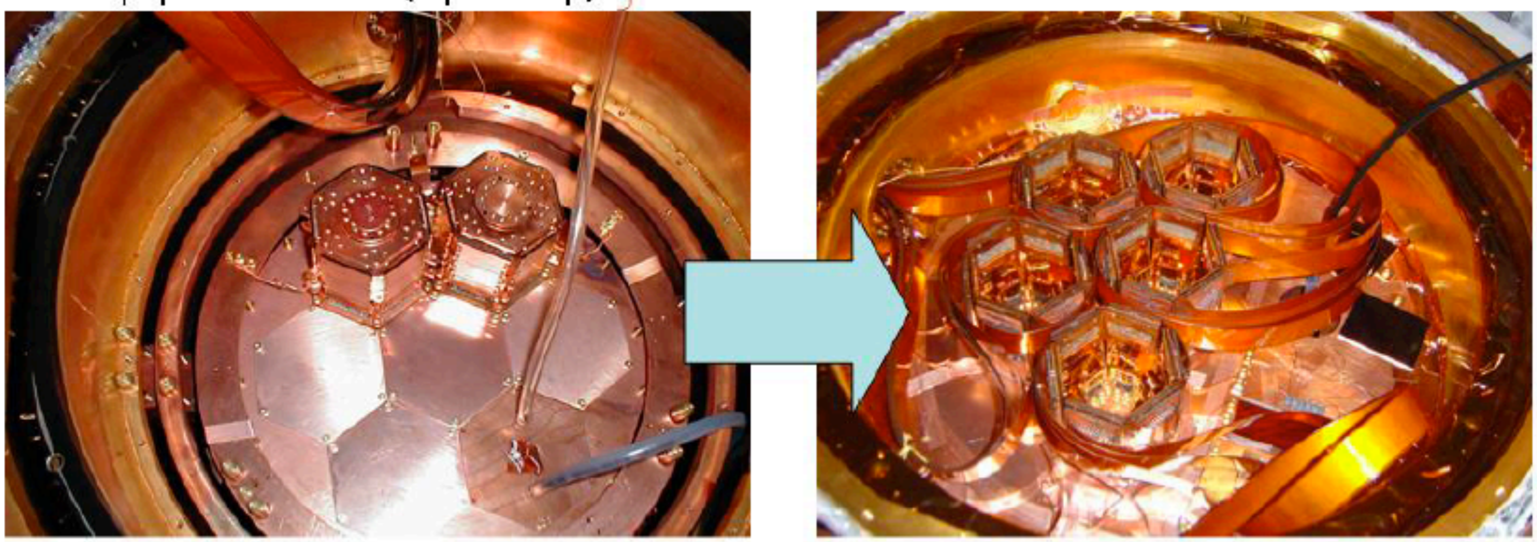
Towers of 6 ZIPs in a stack are kept at 50 mK

Data from the 1 and 2 tower runs

5-tower run is starting now

Astro-ph 0509259 (Spin-Ind)
Astrp-ph 0509269 (Spin-Dep)

Just submitted



TAUP Sept 10-14, 2005
Zaragoza, Spain

Professor Priscilla Cushman
University of Minnesota

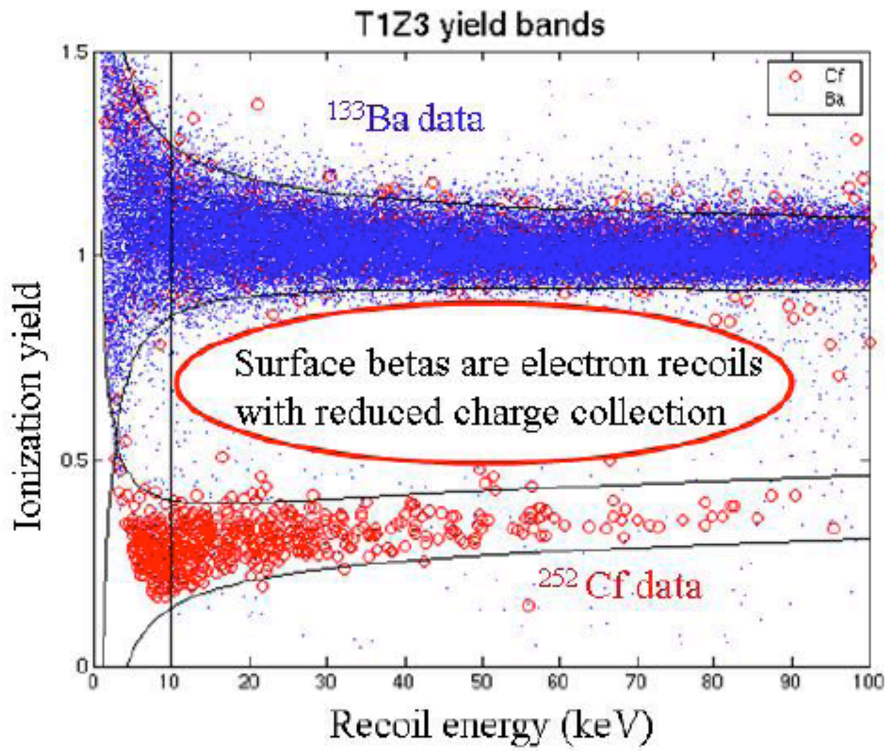
CDMS gets rid of most gammas and betas using the YIELD: ratio of ionization to phonon signal

WIMPs and neutrons produce nuclear recoils with small ionization yield.

Gammas and electrons in the bulk produce electron recoils with ionization yield centered on 1

Calibration source data is used to define 2σ bands (Lindhard functional form)

Surface betas can leak down into the nuclear recoil band



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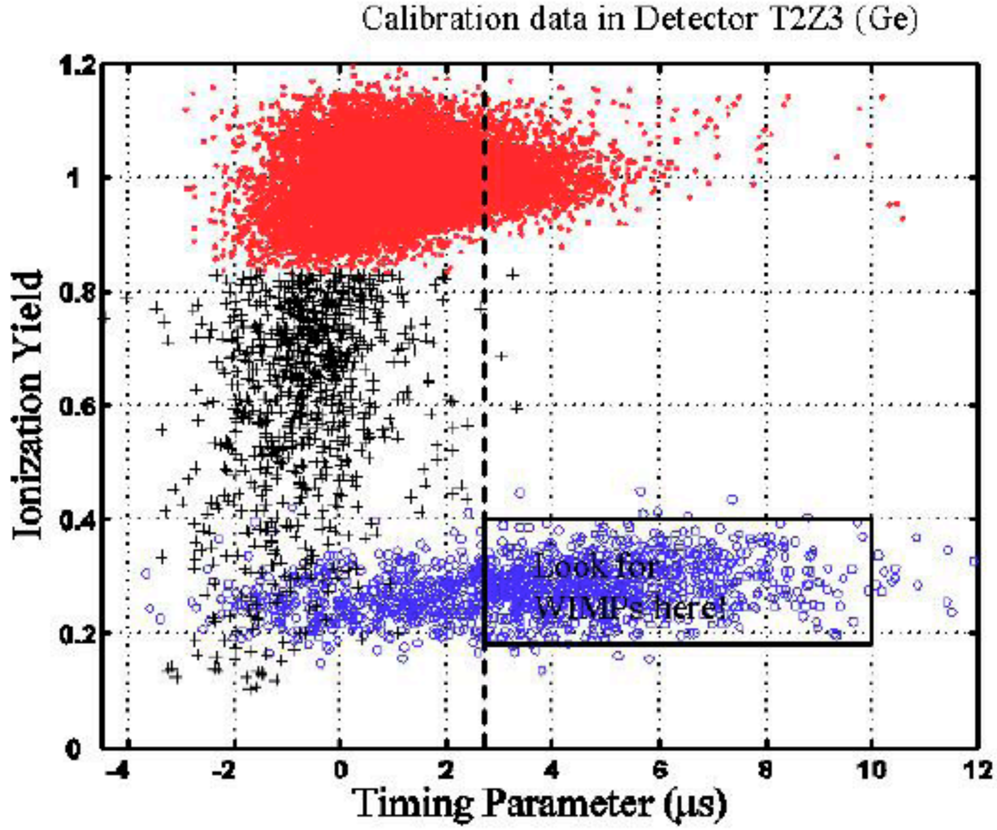
University of Minnesota

Timing provides further discrimination



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University of Minnesota

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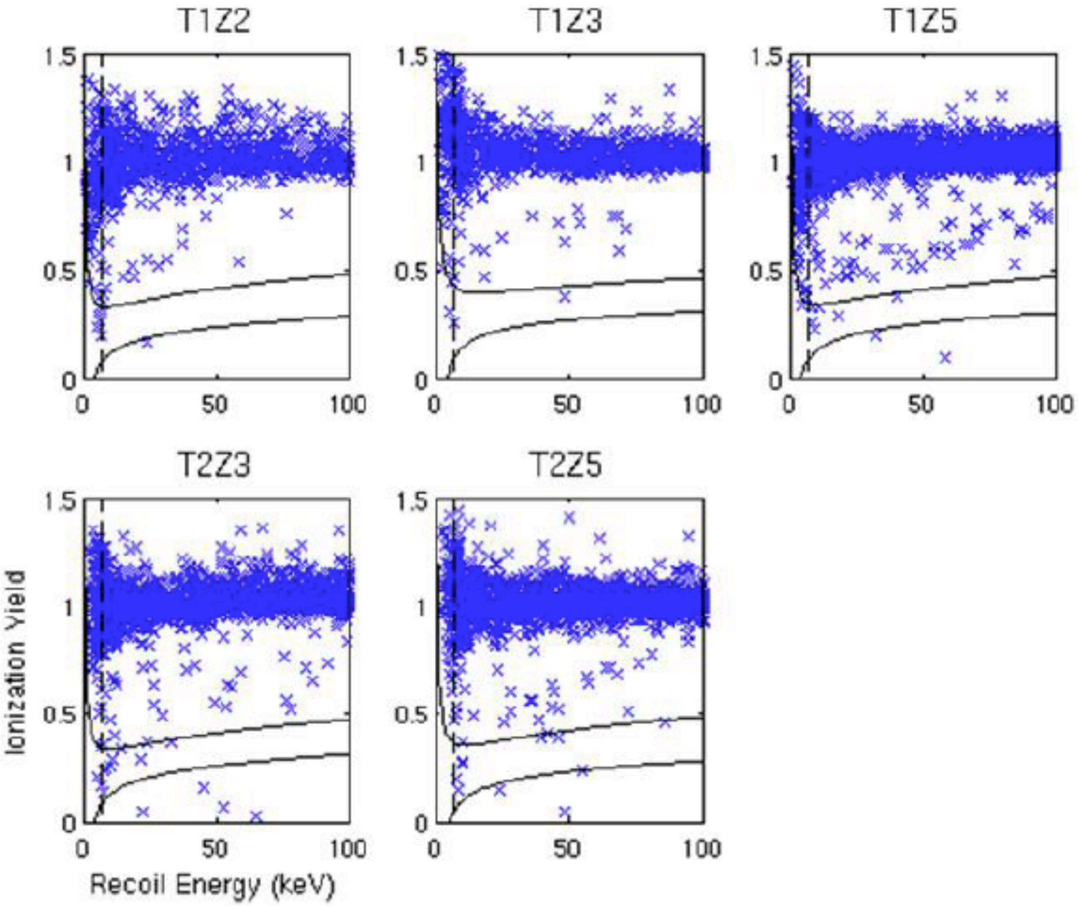
WIMP search data for the Germanium Detectors Before timing cut



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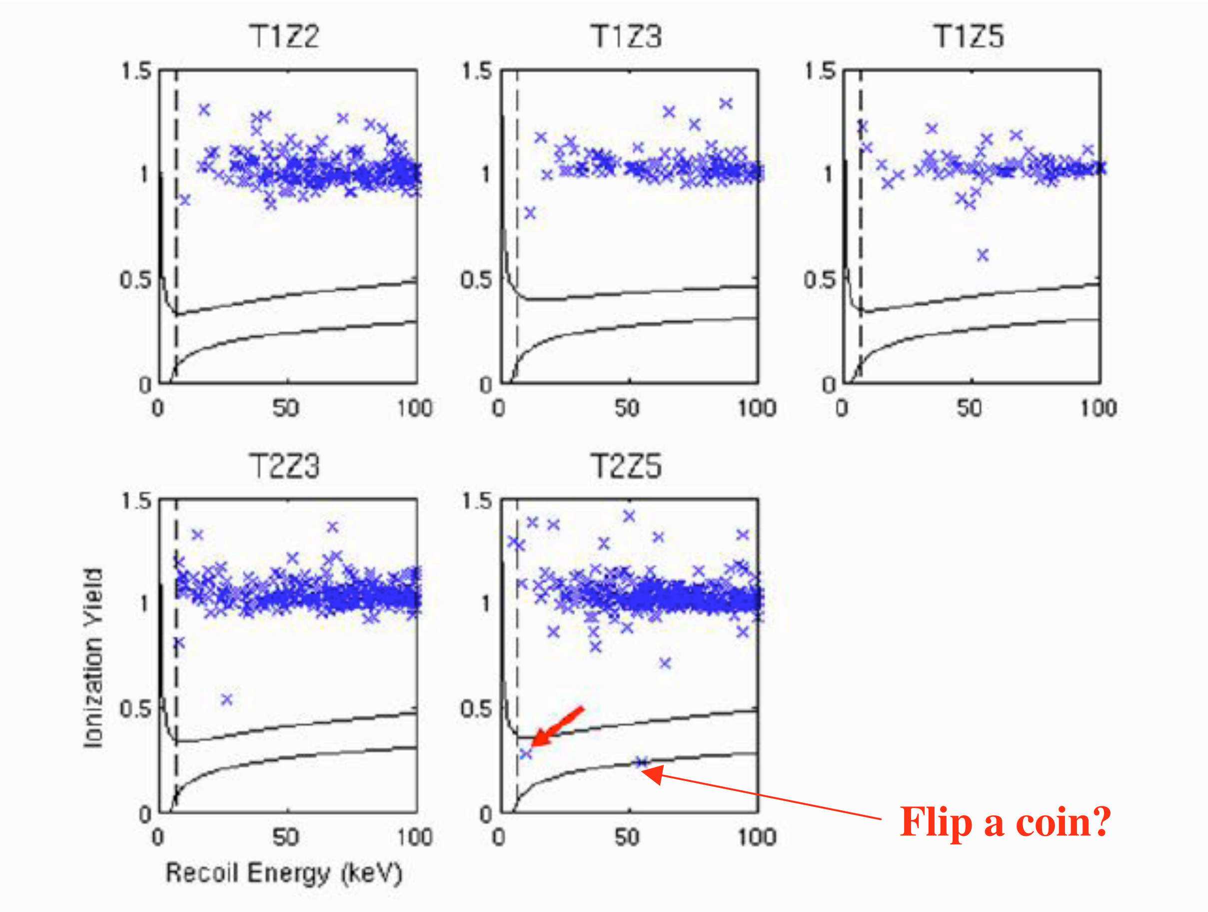
WIMP search data for the Germanium Detectors After timing cut



Flip a coin?

5 tower run with 4 kg of Ge running smoothly.
Exposure increase by ~x10 by end of 2007
First batch of data analysis Mar 07

Two towers of 6 ZIPs each

Close-packed multiple detectors allow identification of multiple scatters
➔ neutrons, NOT WIMPs !

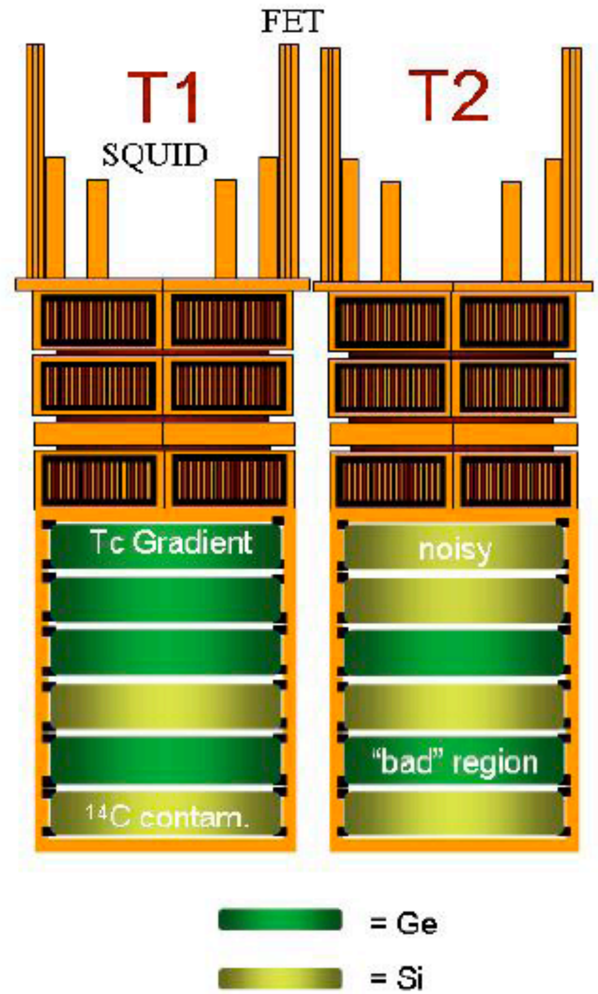
Used 5 Ge (250 g) and 4 Si (100 g)

(Others still provide self-shielding)

Why Silicon if Ge gives best exposure?

WIMP ID

Si has 5-7 times lower WIMP-nucleon rate (but same neutron scattering rate) except for lowest mass WIMPs



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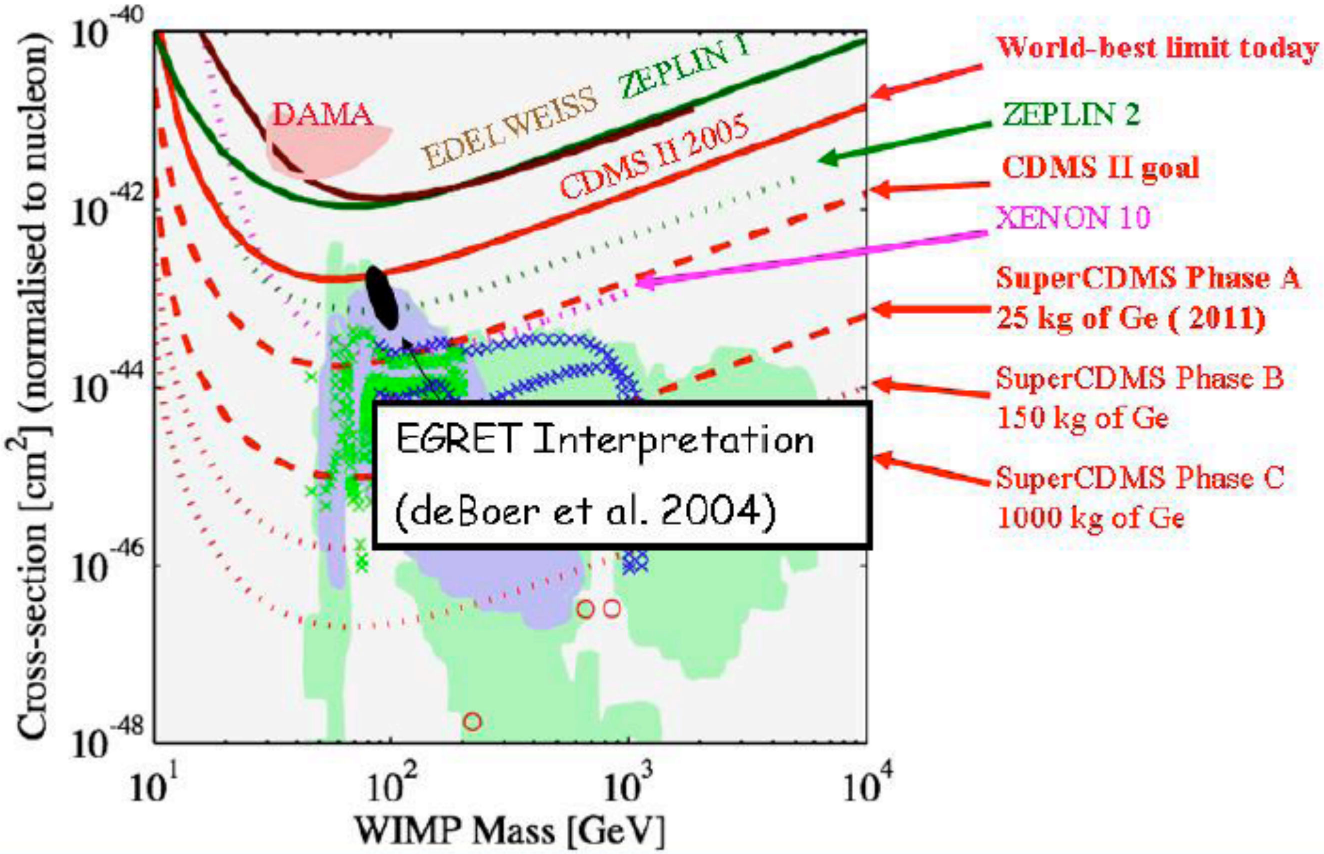
Commercial mass production?

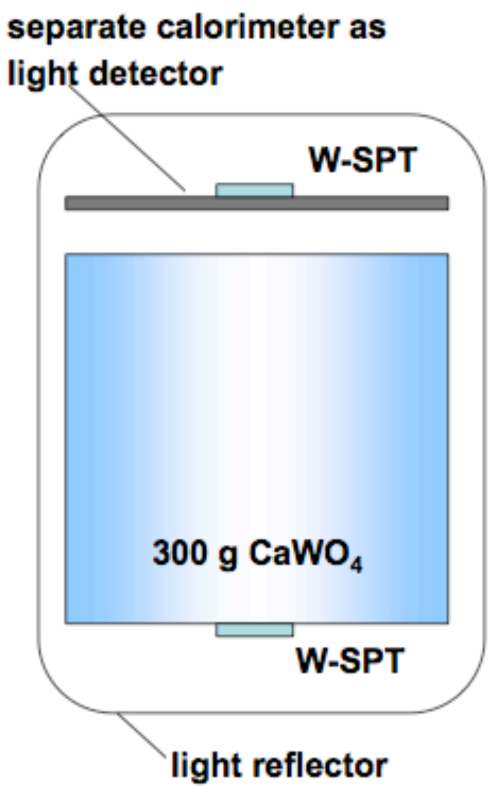
Continuing to probe SUSY space using CDMS

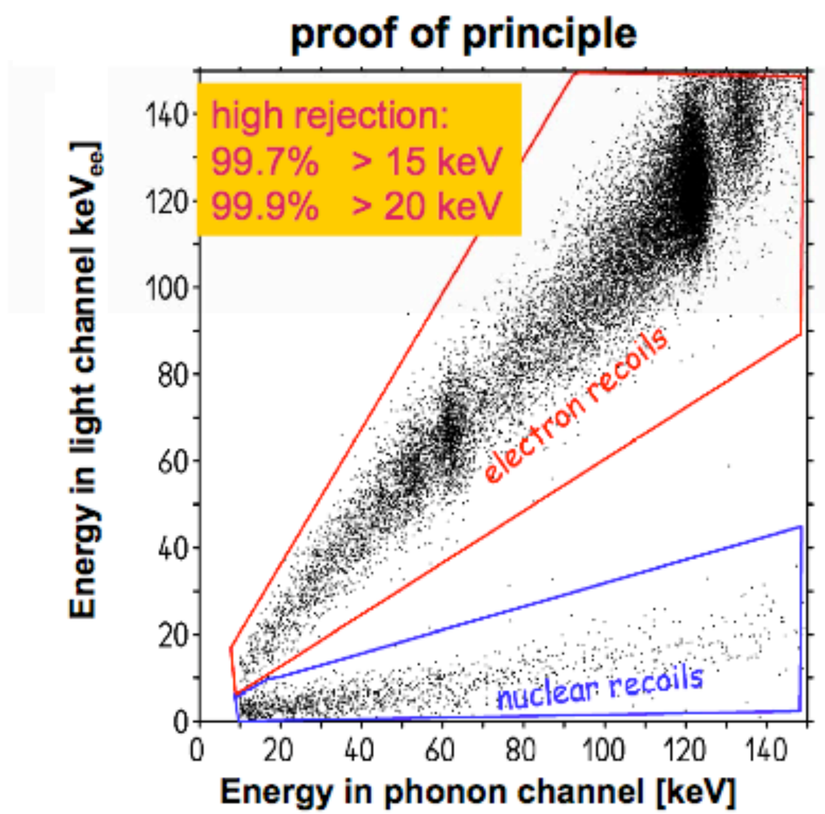


CDMS not alone (CRESST, EDELWEISS...)

Phonon – Scintillation

Discrimination of nuclear recoils from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light





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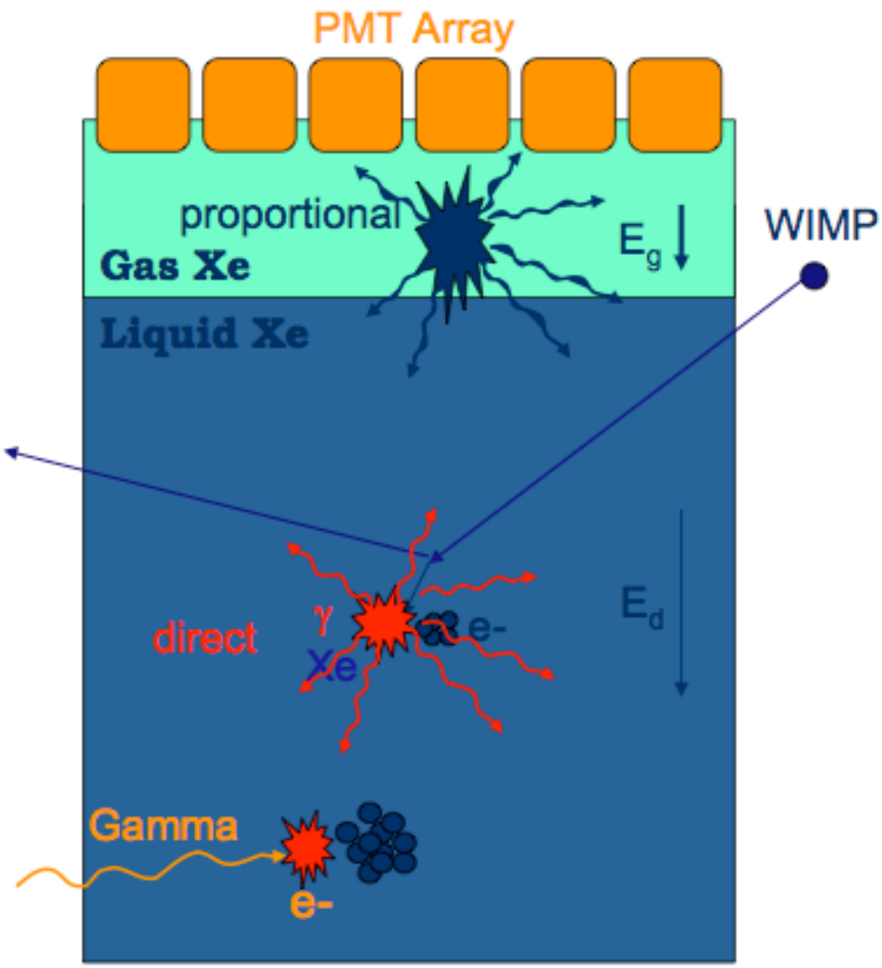
Life is too short.

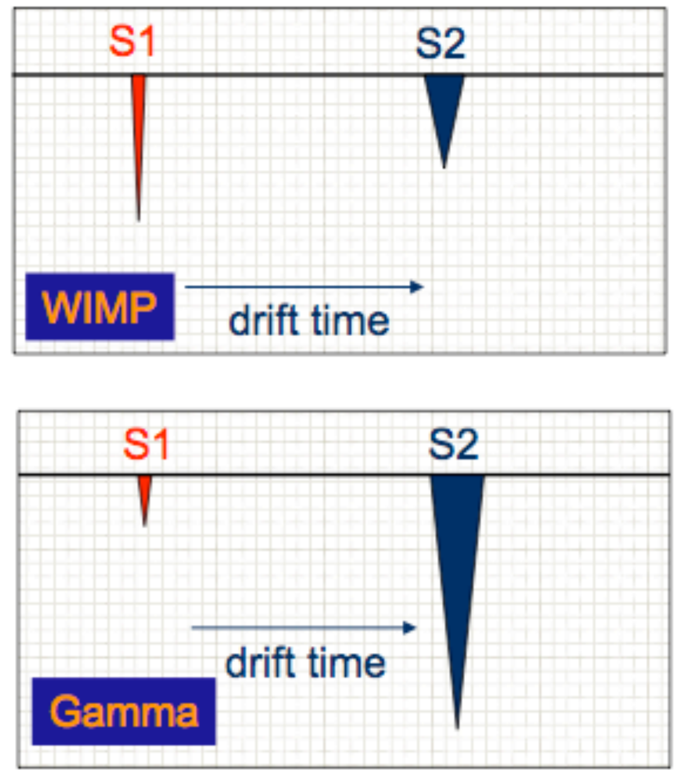
Life is too short.

You can chisel… …or you can pour.

(enter liquid-state contenders)

XENON: Event Discrimination

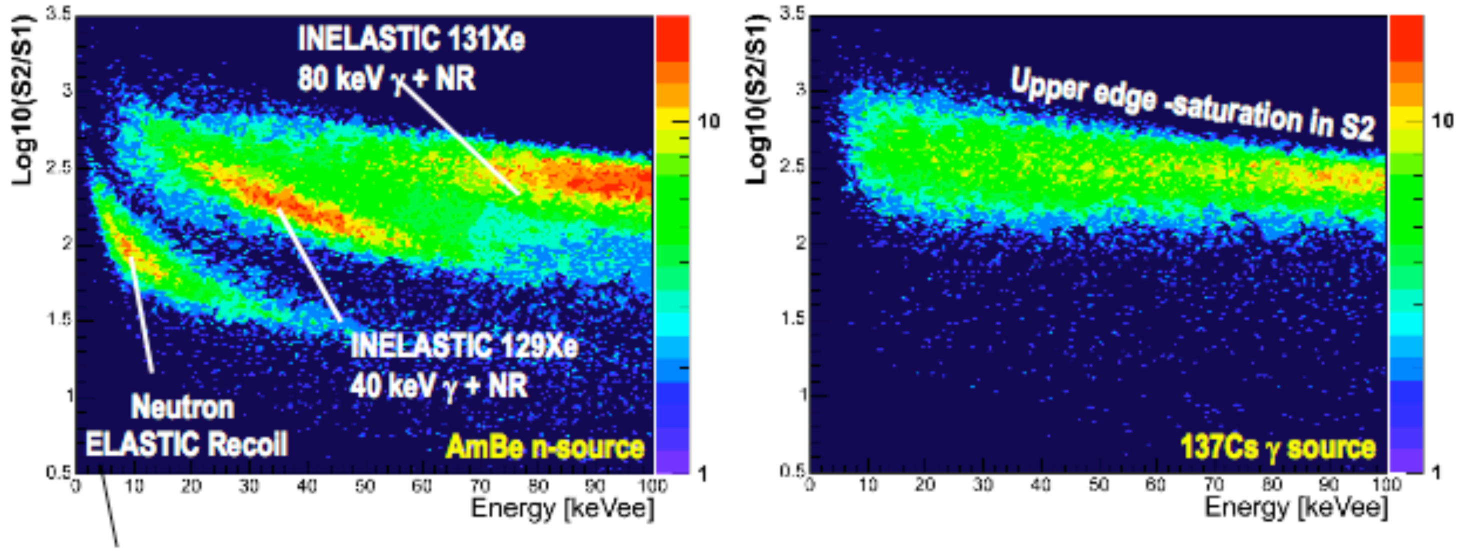




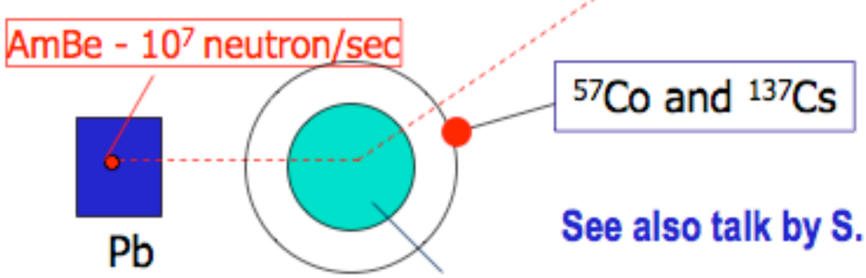
$(S2/S1)_{wimp} \ll (S2/S1)_{gamma}$

EVERY PHOTON IS SACRED

Gamma and Neutron Recoils Discrimination

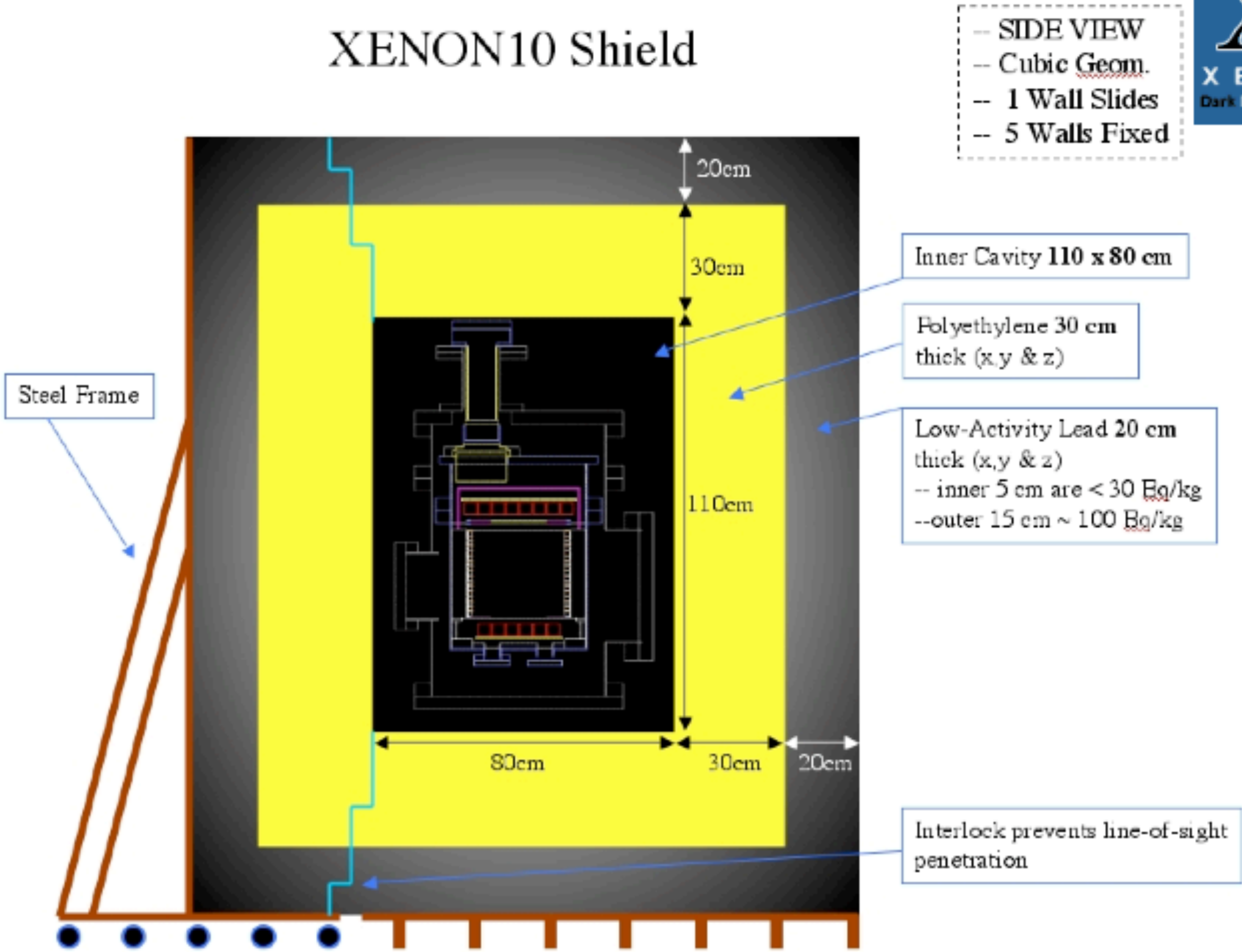


Energy Threshold ER~5 keVee →Recoil Threshold NR~10 keVr



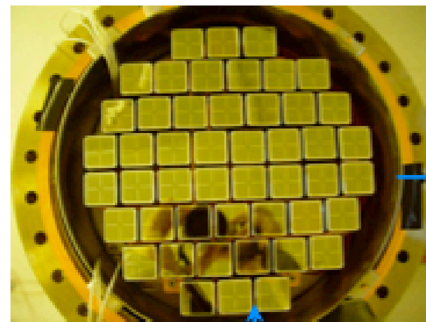
See also talk by S. Kamat for LXe response to neutrons

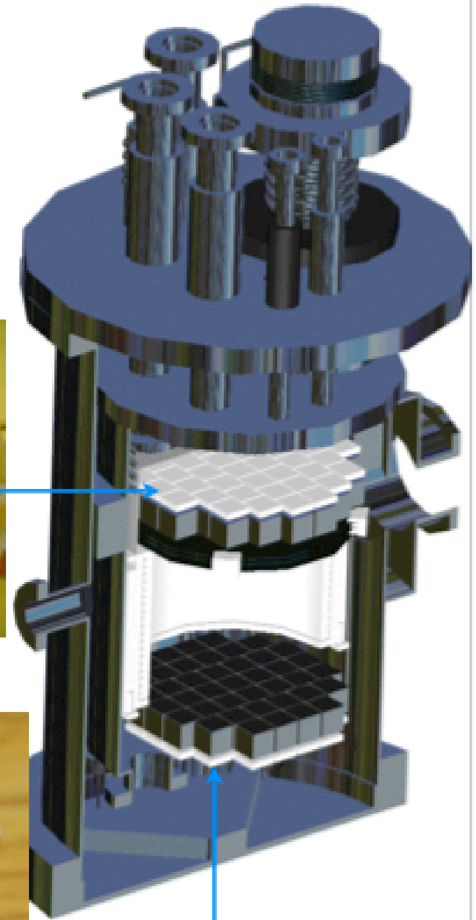
XENON10 Experimental Setup at LNGS

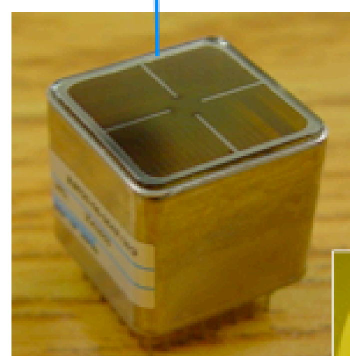


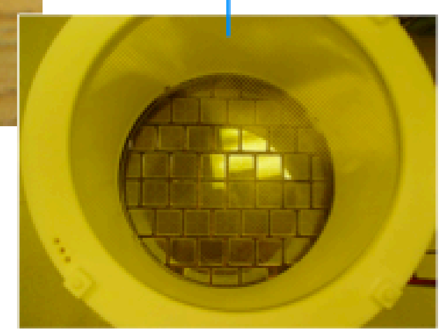
The XENON10 Detector

- **22 kg of liquid xenon**
  - ➡15 kg active volume
  - ➡20 cm diameter, 15 cm drift
- **Hamamatsu R8520 1”×3.5 cm PMTs**
  bialkali-photocathode Rb-Cs-Sb,
  Quartz window; ok at -100ºC and 5 bar
  Quantum efficiency > 20% @ 178 nm
- **48 PMTs top, 41 PMTs bottom array**
  - ➡x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx 1$ mm
  - ➡z-position from Δt_{drift} ($v_{d,e\text{-}} \approx 2$mm/µs), $\sigma_Z \approx 0.3$ mm
- **Cooling: Pulse Tube Refrigerator (PTR),**
  90W, coupled via cold finger (LN_2 for emergency)



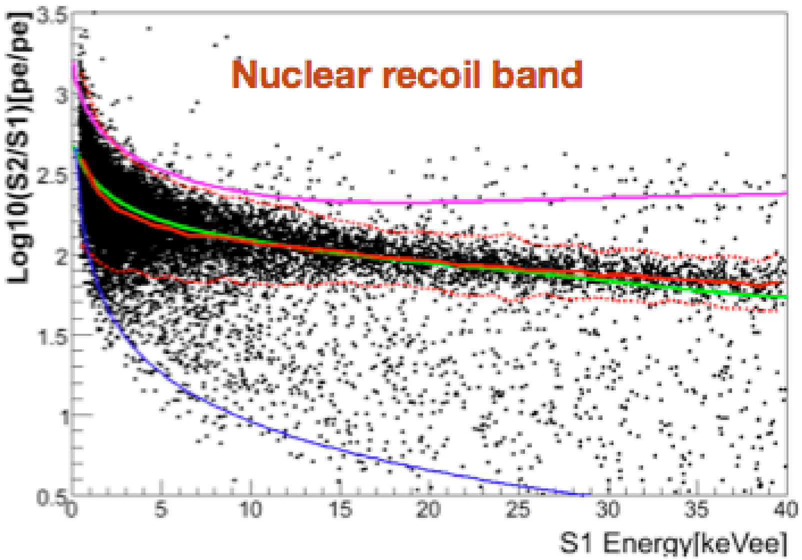


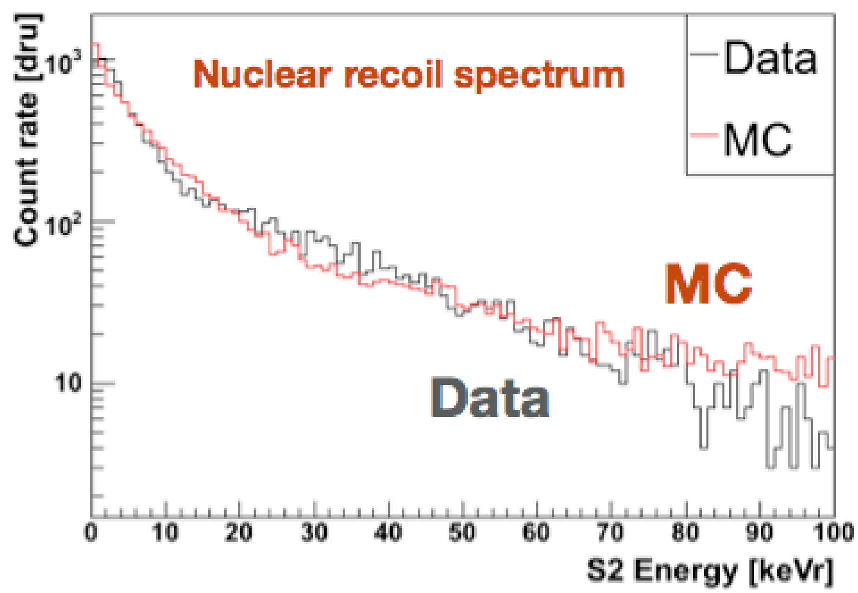




XENON10 Neutron Calibration

- Neutron source: AmBe (E_{max} = 4 MeV)
- In situ calibration: December 1, 06 => determination of the nuclear recoil band
  - ➡Background rejection analysis in progress





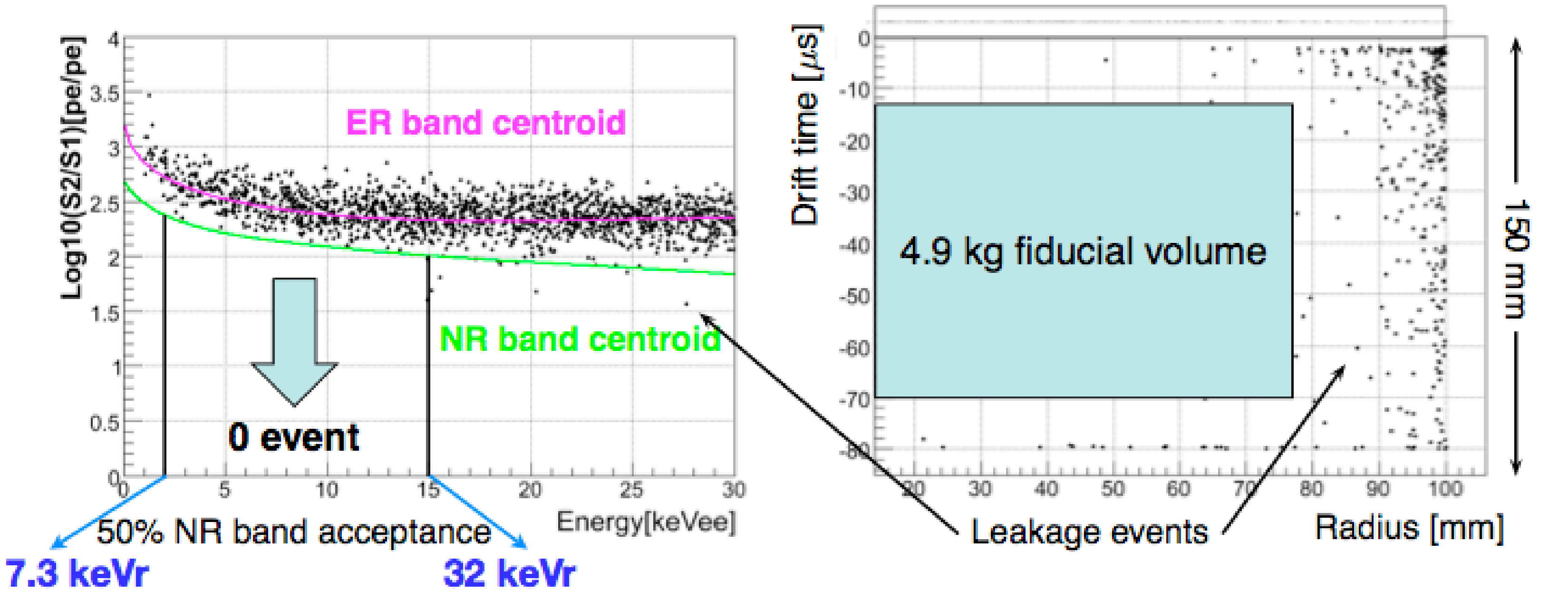
Green: **NR band from smaller CWRU detector** (T. Shutt et al., DM2006 proceedings, astro-ph/0608137)

⇒ good agreement between NR centroids!

⇒ NR response at low energies well understood

XENON10 Preliminary WIMP Search Data

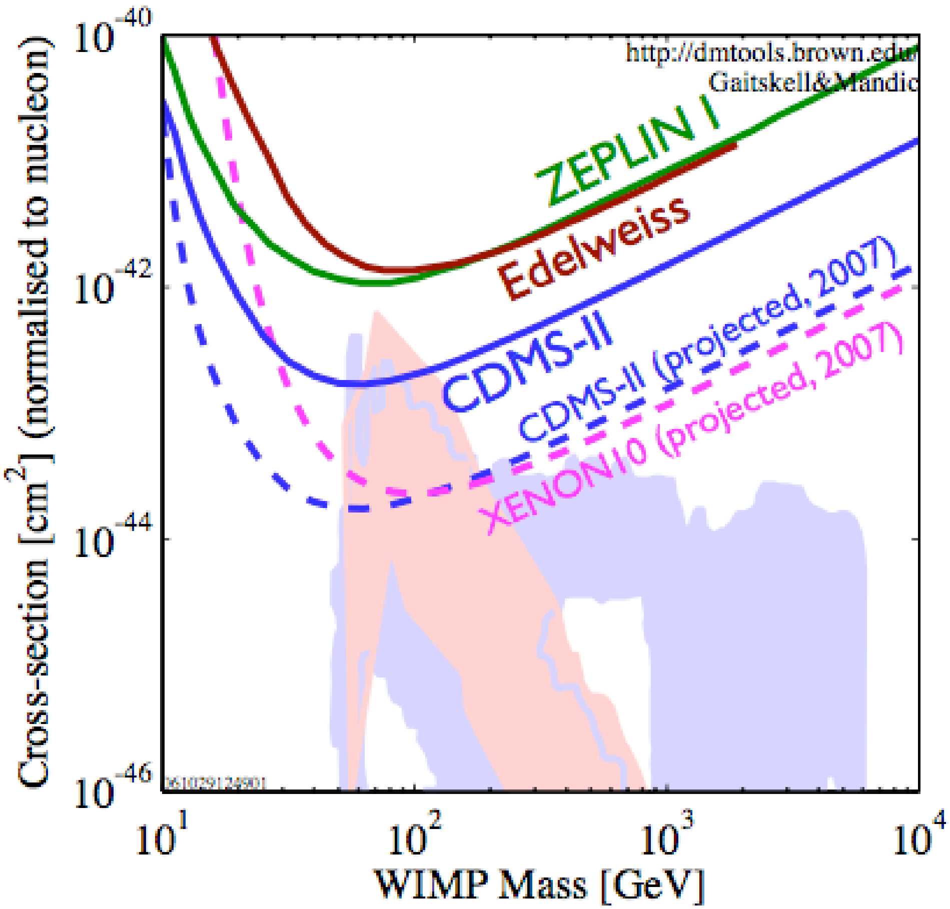
- WIMP search run started Aug. 24. 2006: $>10^6$ events, > 40 live days
- 2 independent analysis groups (root and matlab based)
- Example: preliminary data from ~ 17 live days



- Full analysis in progress; understand source of leakage events; set cuts and calculate efficiencies based on γ- and n-calibration data,...

XENON10 WIMP Search Goals

- Test the elastic, SI WIMP-nucleon σ down to ≈ 2×10^{-44} cm^2 in 2007



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From the people that brought you this beauty...

G. Fiorillo / Nuclear Physics B (Proc. Suppl.) 150 (2006) 372–376 373

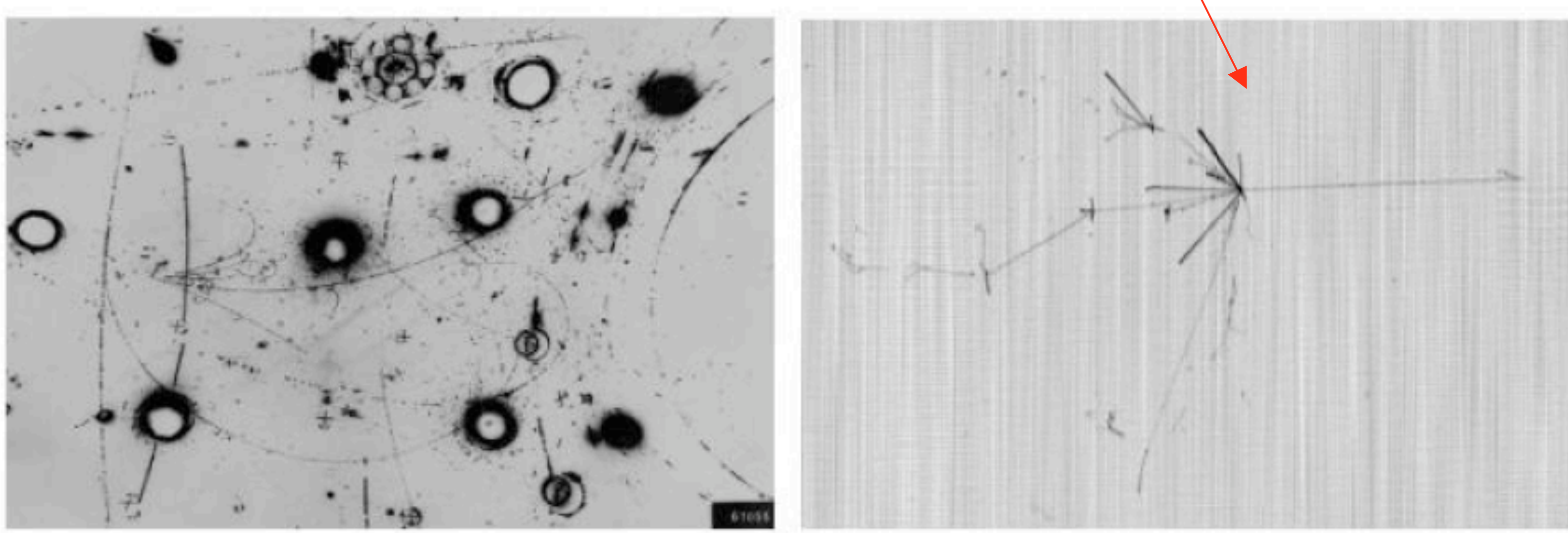
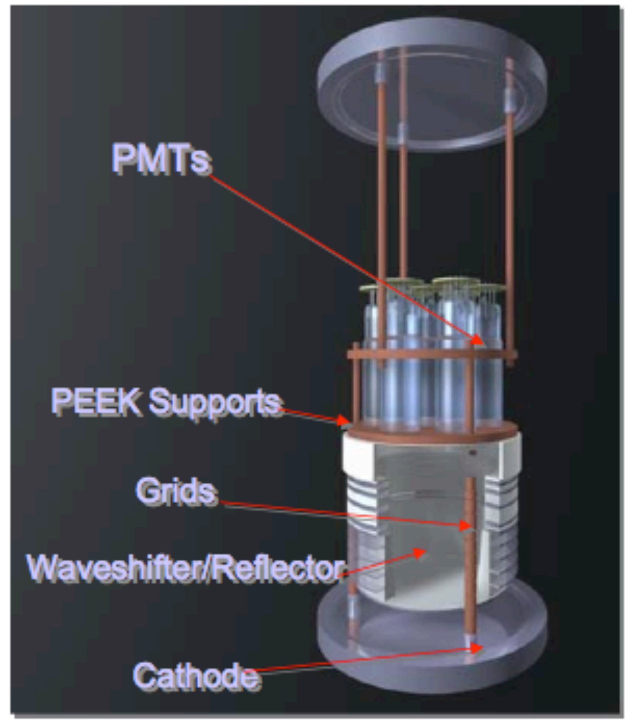


Figure 1. Electronic bubble chamber: an event recorded by the Gargamelle bubble chamber (left) compared to an hadronic interaction collected in the ICARUS TPC during the technical run on the surface (right).

What's a couple of kilos next to 600T?
(in less than 2 yr, $>10^7$ rejection!!!)

The WARP 2.3 liters test

- The 2.3 liters prototype has been equipped, in subsequent phases, with 2" and 3" PMs made of low background materials.
- The structure is a (down) scaled version of the 100 liters detector, with field-shaping electrodes and gas to liquid extraction and acceleration grids.
- The equipment is contained in a high-vacuum tight container immersed into an external, refrigerating, liquid argon bath.
- The chamber is filled with ultra-purified argon in order to allow for long drift times of free electrons.
- Puritiy is maintained stable by means of continuous argon recirculation.



Schematic view of the 2.3 liters chamber

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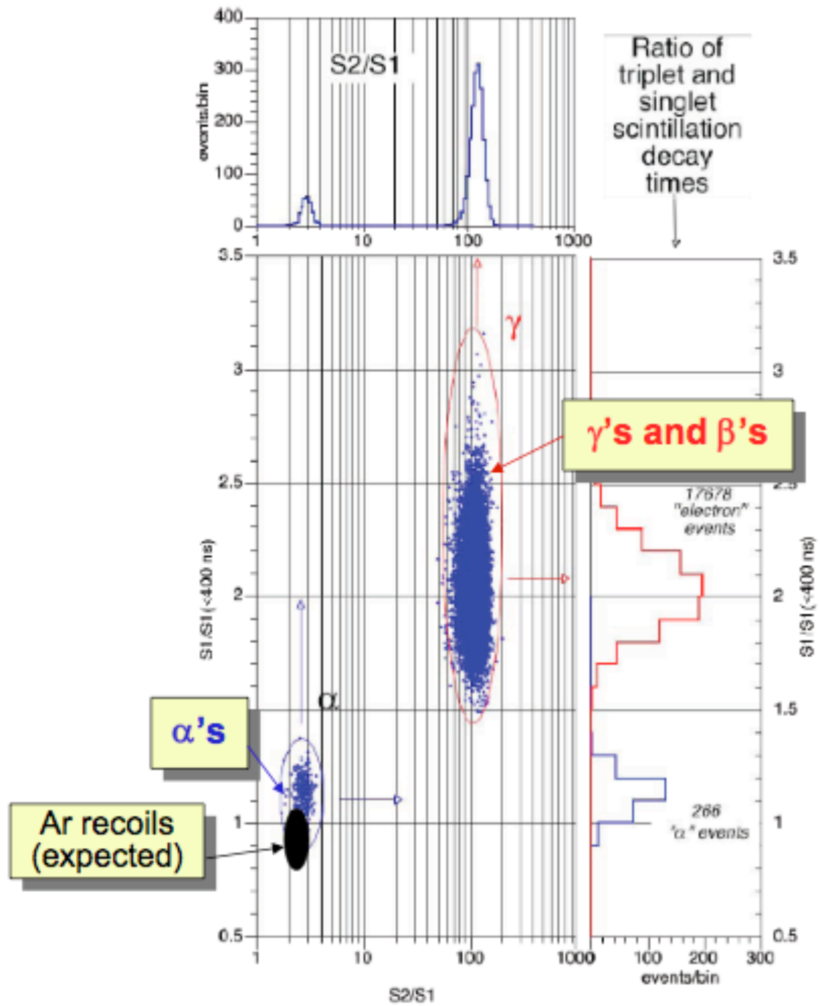
What's a couple of kilos next to 600T?
(in less than 2 yr, $>10^7$ rejection!!!)



The combination of a selection based on S2/S1 ratio and rise time of primary scintillation gives an extremely poweful rejection power for the search of WIMPs signals.

No event outside the two circled regions

Complete agreement up to an observed level of ≈ 1/20000 ➔ combined rejection < $1/10^8$

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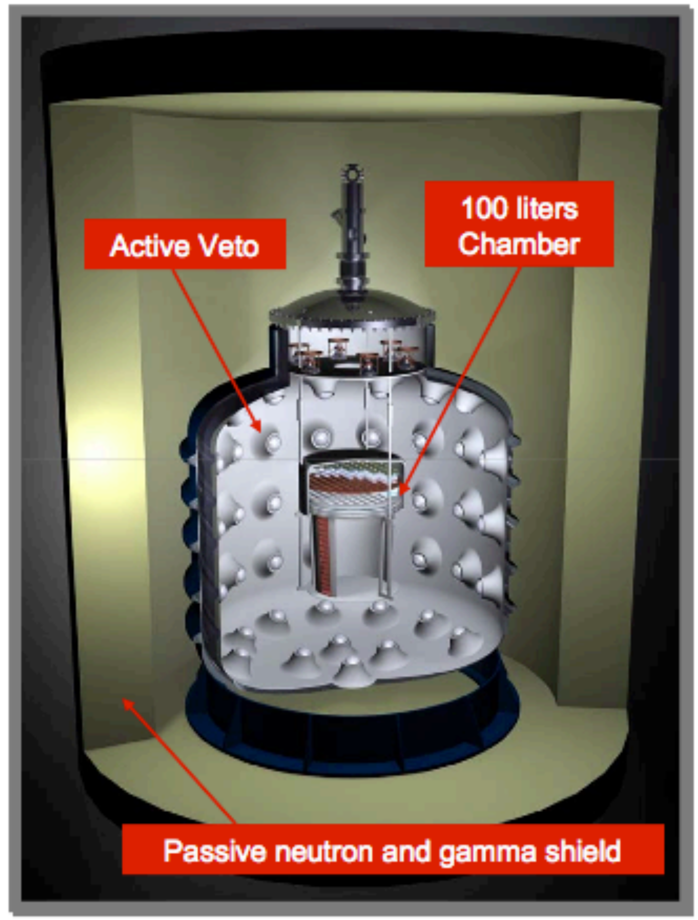
Looming over the horizon...

The WARP 100 liters chamber

- The liquid argon final detector with a sensitive volume of 100 liters is expected to be operational by 2006.
- In order to perfect the detection method, a 2.3 liters test jig is in operation at the LNGS, since April 2004.
- It is expected that the test detector may already reach competitive sensitivity levels.
- The 100 liters detector will provide, in addition to the increased sensitive mass:
  - the active VETO system, completely surrounding the 100 litres sensitive volume;
  - 3-D event localization by means of:
    - Drift time recording (vertical axis);
    - Centroid of PM's secondary signal amplitudes (horizontal plane).



Less is more: XMASS
(this from the people that brought you Super-K...)

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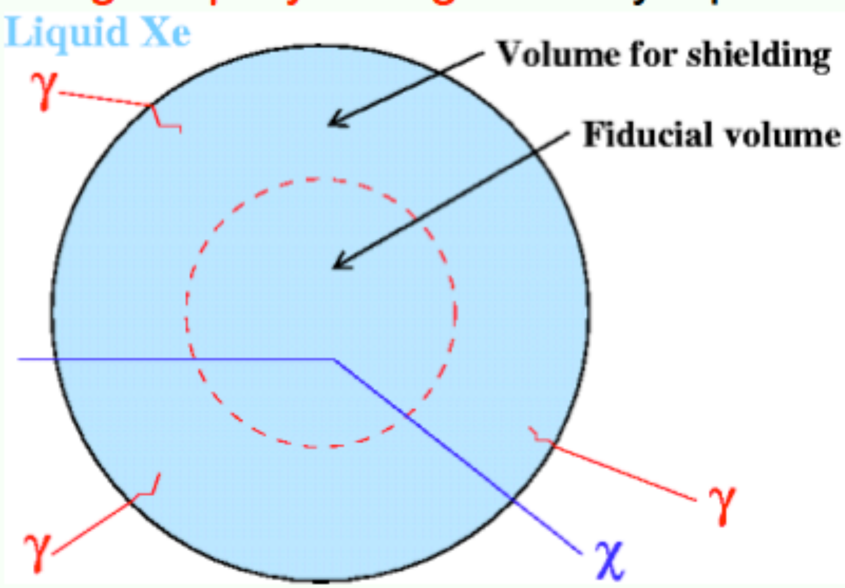
- Key idea

Self shielding for γ ray background by liquid Xe (Z=54)



Reconstruct the vertex of events from PMTs information

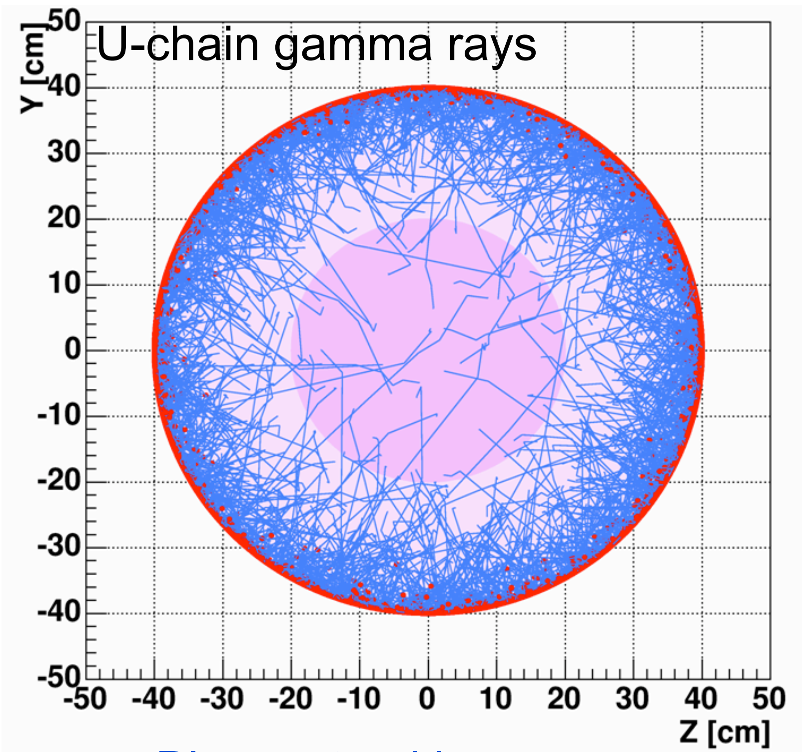
→ γ ray backgrounds are absorbed in outer volume

→ Dark matter can go into fiducial volume

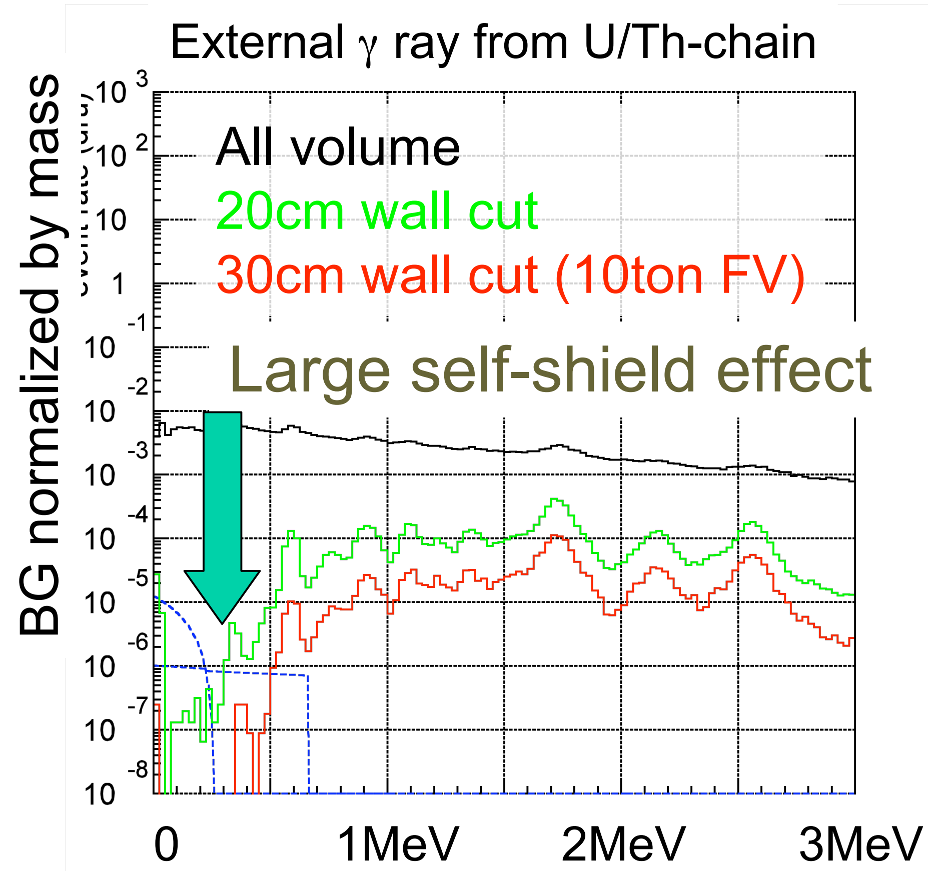
XMASS

Key idea:
self-shielding effect for low energy events

γ tracking MC from external to Xenon

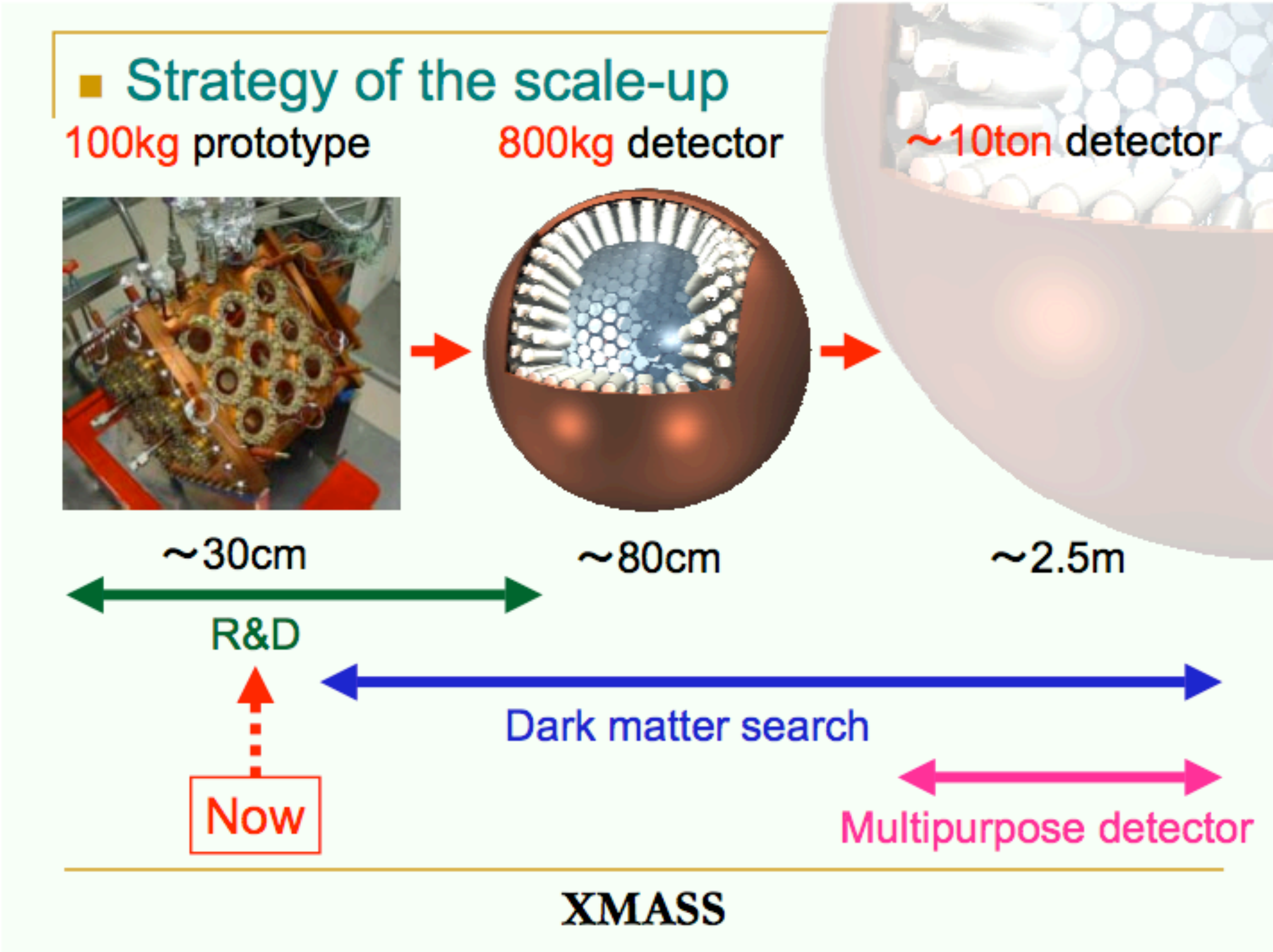


Blue : γ tracking
Pink : whole liquid xenon
Deep pink : fiducial volume



Background are widely reduced in < 500keV low energy region

Be scared. Be really, really scared.



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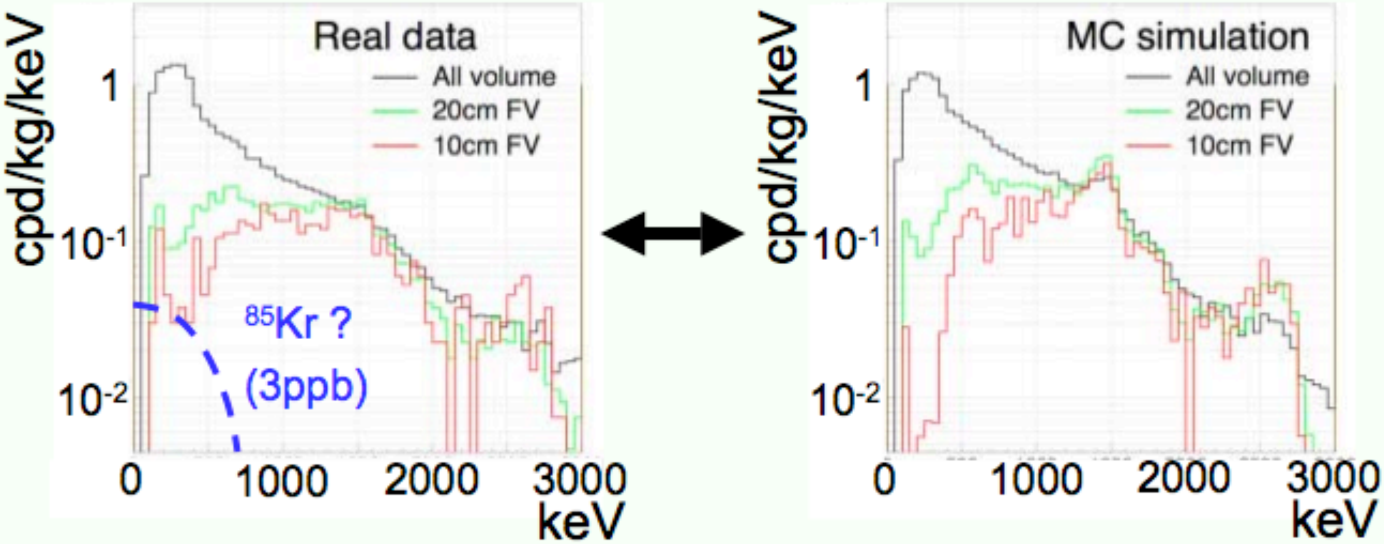
These people mean business.

Self shielding for real data and MC



☆ Low background at inner volume by self shielding

→ Good agreement real data and MC estimation

☆ Something exists in low energy region of the real data

→ Internal background (^{85}Kr?)

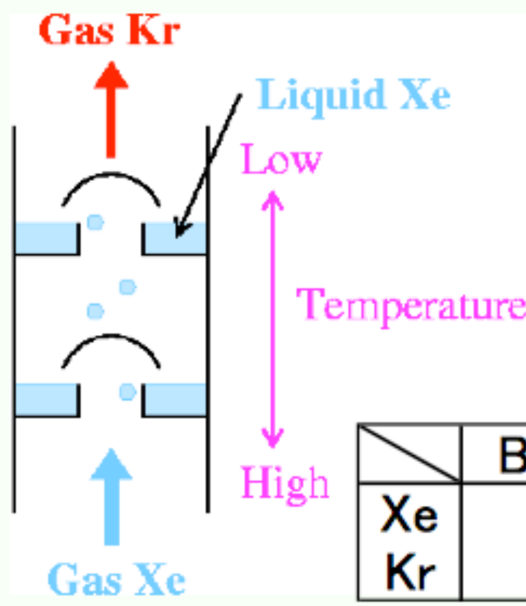
XMASS

Yes, they do.

Purification of Xe by distillation

☆ Test using 1.6kg Xe in September 2003

☆ XMASS succeeds to reduce Kr concentration in Xe from 310[ppb] to < 5[ppb] with one cycle (~1/100)



	Boiling point
Xe	165K
Kr	120K

→ Full process of 100kg Xe next week!

XMASS

Oh, shucks.

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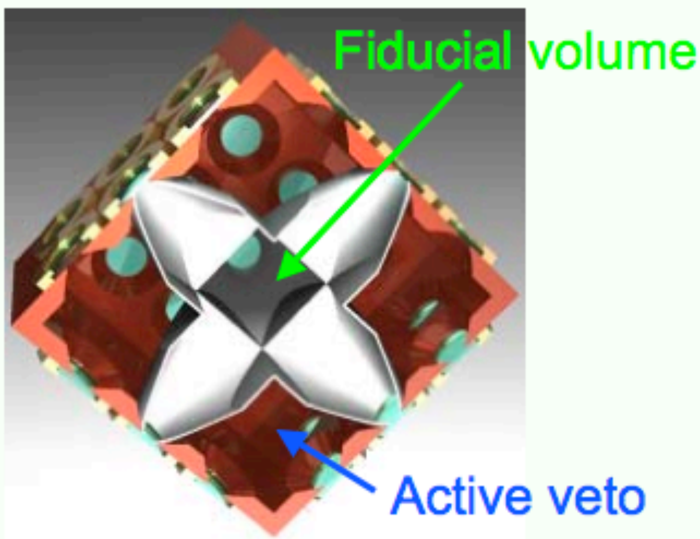
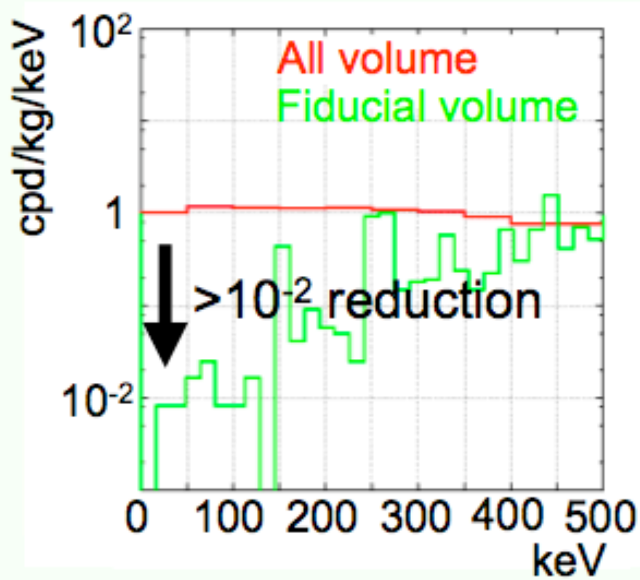
Next plan of 100kg detector (2)

☆ Dark matter search with PTFE light guide

- 0.6 p.e./keV → 1.2 p.e./keV
- Difficult to fit the wall events → No need to fit





→ Reach the sensitivity of DAMA, CDSM,…

XMASS

Status of 800 kg detector

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- **Basic performances have been already confirmed using 100 kg prototype detector**
  - ✓ Vertex and energy reconstruction by fitter
  - ✓ Self shielding power
  - ✓ BG level

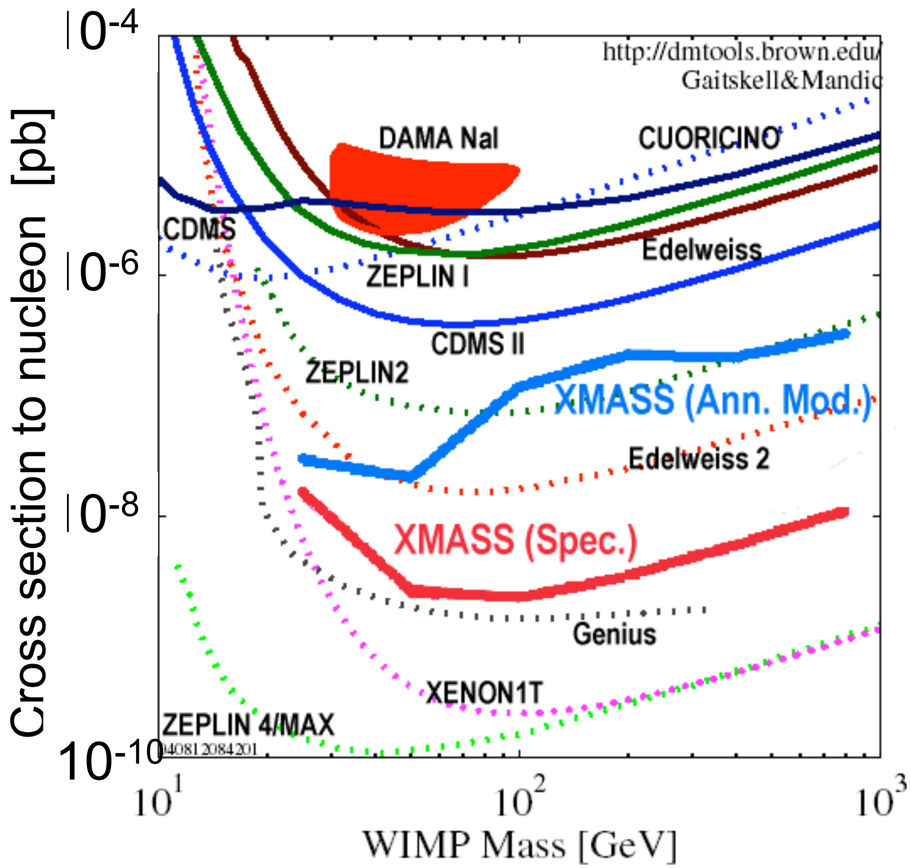
- **Detector design is going using MC**
  - ✓ Structure and PMT arrangement (812 PMTs)
  - ✓ Event reconstruction
  - ✓ BG estimation

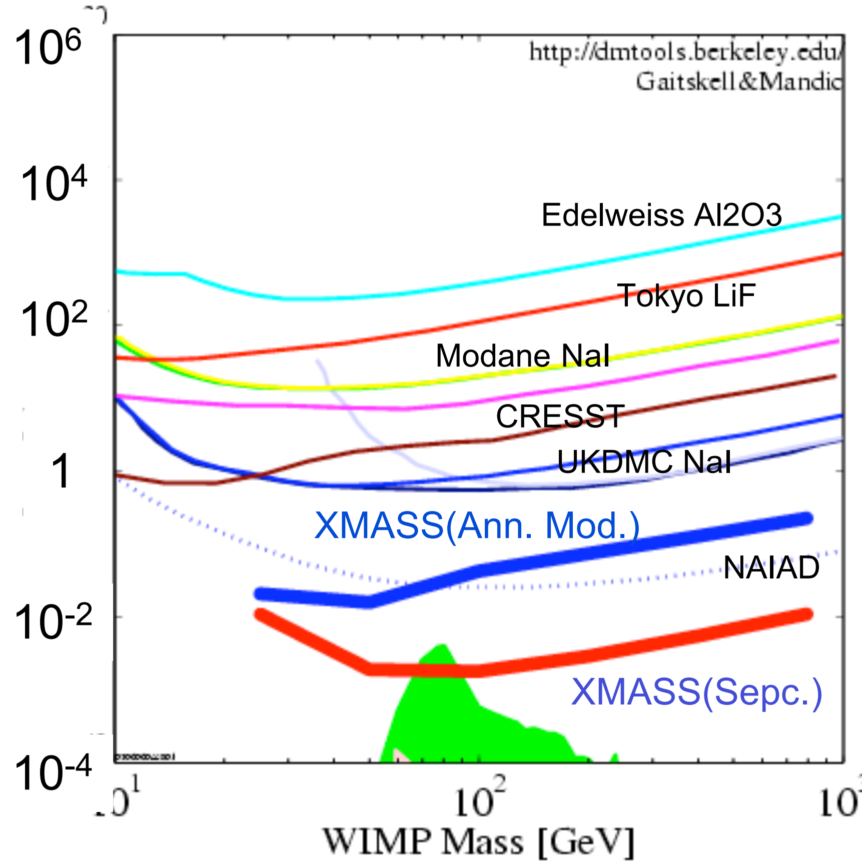
- **New excavation will be done soon**
  - ✓ Necessary size of shielding around the chamber

Expected sensitivities

for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

XMASS FV 0.5 ton year
E_{th} = 5 keVee~25 p.e., 3σ discovery
w/o any pulse shape info.





- Large improvements will be expected
  SI ~ 10^{-45} cm^2 = 10^{-9} pb
  SD~ 10^{-39} cm^2 = 10^{-3} pb

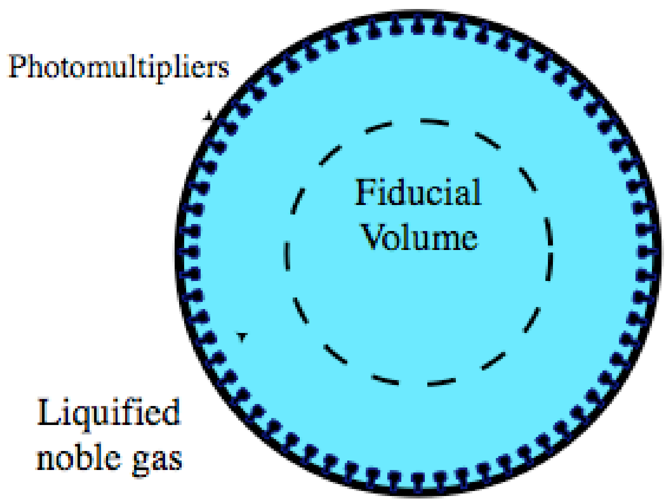
Plots except for XMASS:
http://dmtools.berkeley.edu
Gaitskell & Mandic

The Mini-CLEAN Approach

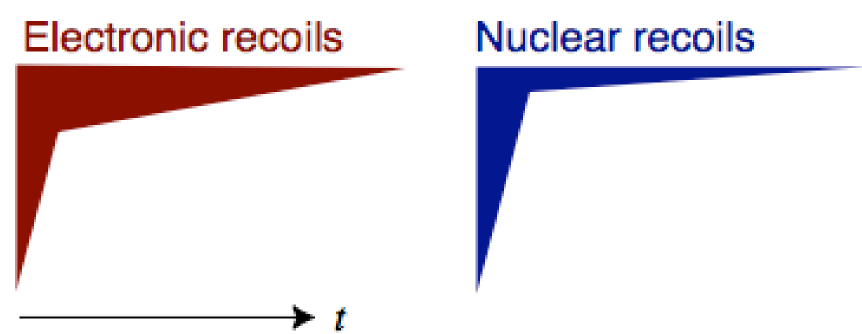
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

Liquid neon and liquid argon are bright scintillators (30,000 - 40,000 photons/MeV).
Do not absorb their own scintillation.
Are inexpensive.
Are easily purified underground.
Exhibit effective pulse shape discrimination.
Exchange of targets allows better characterization of radioactive backgrounds

Self-shielding



Pulse-shape discrimination

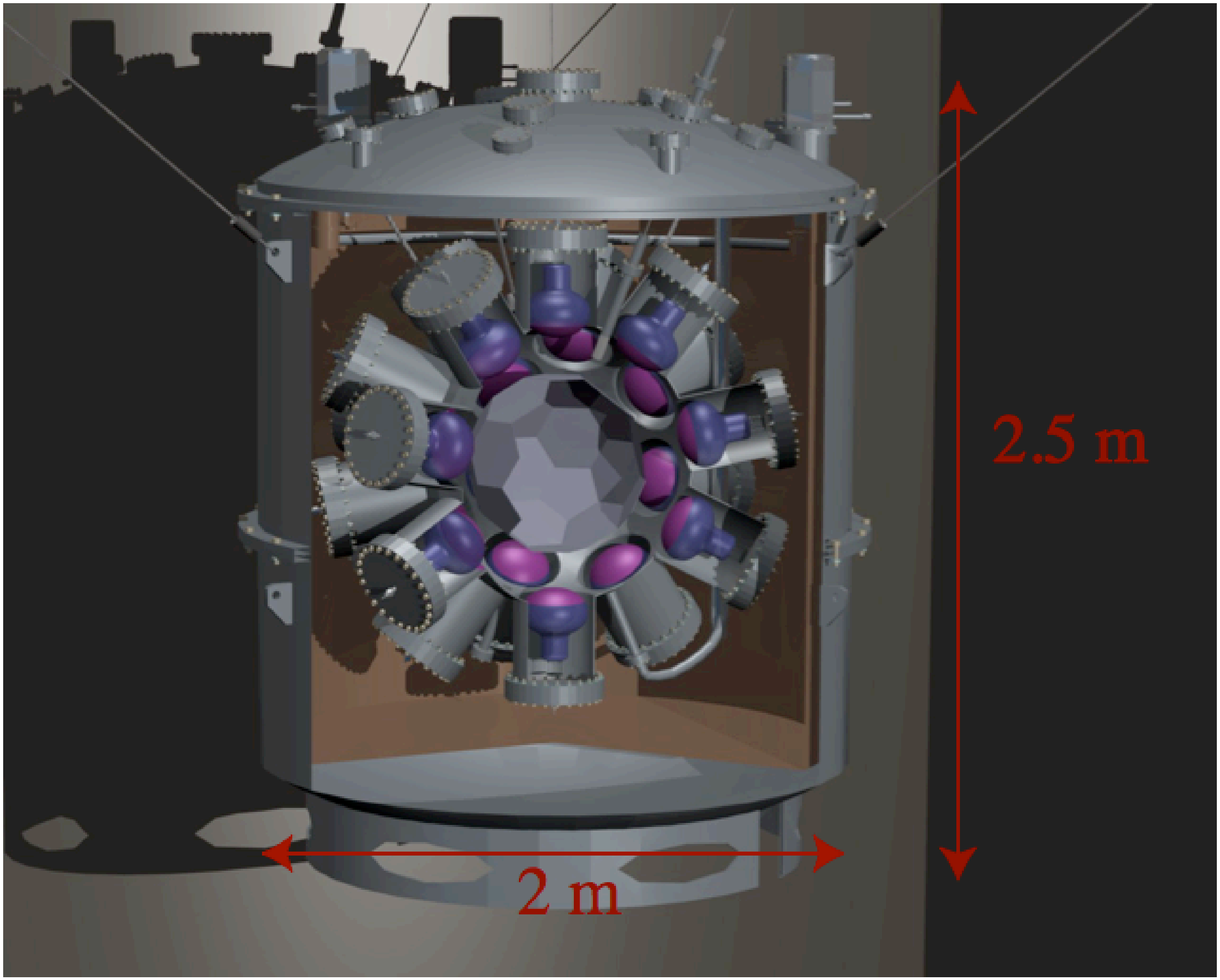


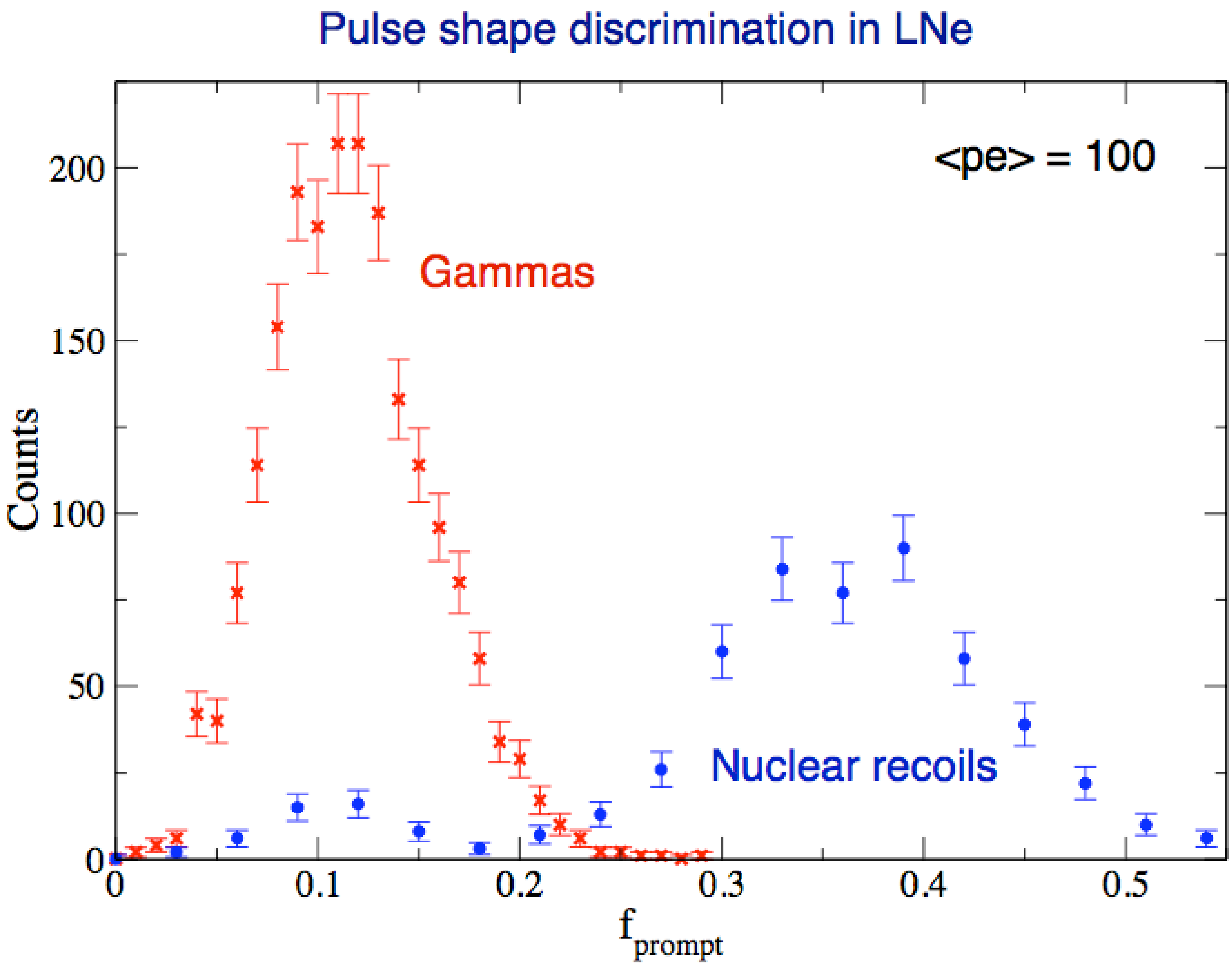
Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

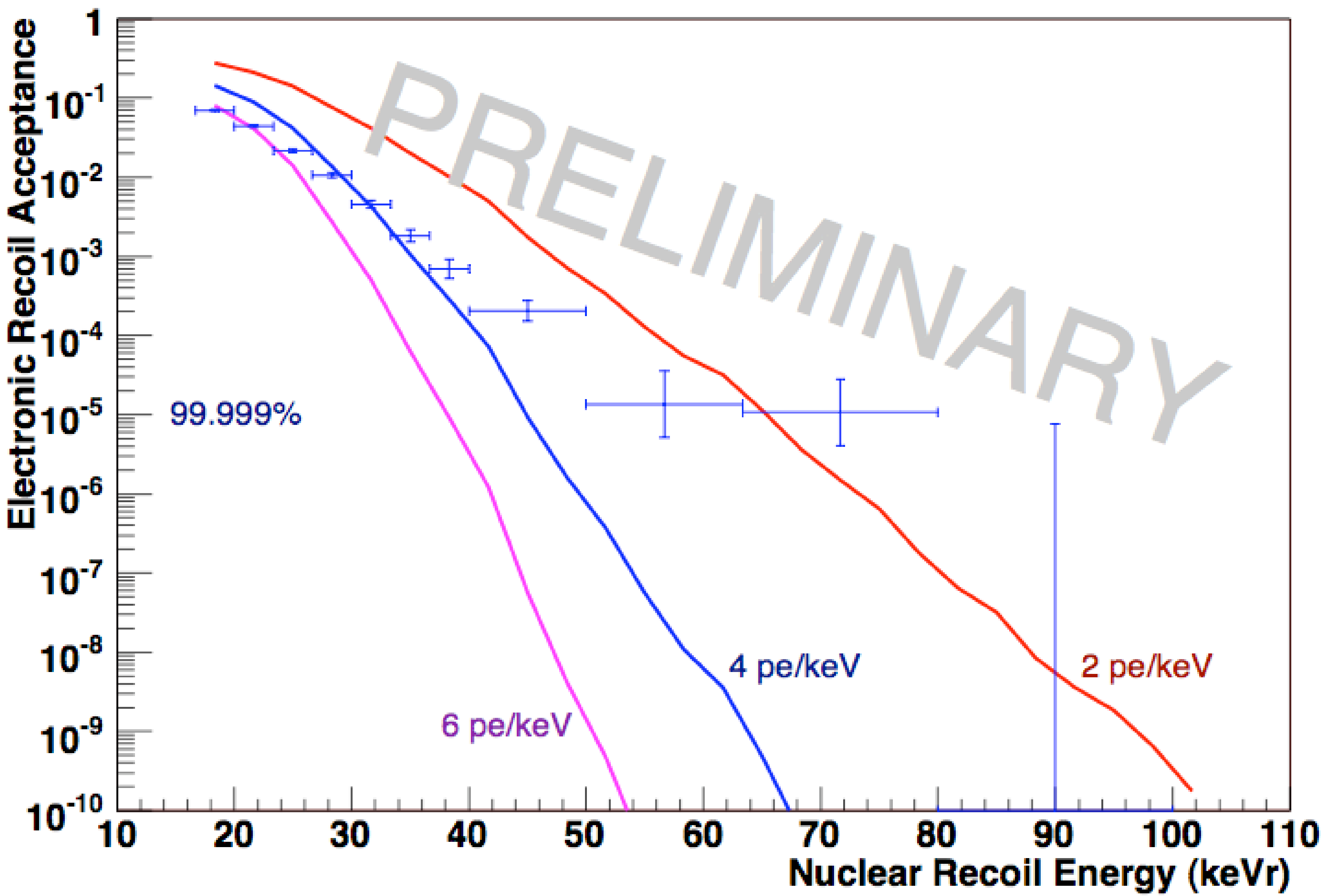
Mini-CLEAN at 100 kg scale

Active mass: 100 kg of LAr or LNe.   Expected signal yield > 6 pe/keV




Pulse shape discrimination in LNe
<pe> = 100
Gammas
Nuclear recoils
Counts
0
50
100
150
200
0
0.1
0.2
0.3
0.4
0.5
f_prompt

Electronic Recoil - Nuclear Recoil Discrimination Efficiency vs Energy in LAr
First tests of LAr PSD at energies relevant to WIMP search
Discrimination measurement limited by neutron backgrounds in surface laboratory



KICP
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COUPP approach to WIMP detection:

- Detection of single bubbles induced by high-dE/dx nuclear recoils in heavy liquid bubble chambers

- $>10^{10}$ rejection factor for MIPs. *INTRINSIC* (no data cuts)

- Scalability: large masses easily monitored (built-in "amplification"). Choice of three triggers: pressure, acoustic, motion (video))

- Revisit an old detector technology with improvements leading to extended (unlimited?) stability (*ultra-clean* BC)

- Excellent sensitivity to both SD and SI couplings (CF_3I)

- Target fluid can be replaced (e.g., C_3F_8, C_4F_{10}, CF_3Br). Useful for separation between n- and WIMP-recoils and pinpointing WIMP in SUSY parameter space.

- High spatial granularity = additional n rejection mechanism

- Low cost (<350 USD/kg target mass *all inclusive*), room temperature operation, safe chemistry (fire-extinguishing industrial refrigerants), moderate pressures (<200 psig)

- Single concentration: reducing α-emitters in fluids to levels already achieved elsewhere (~10^{-17}) will lead to complete probing of SUSY models

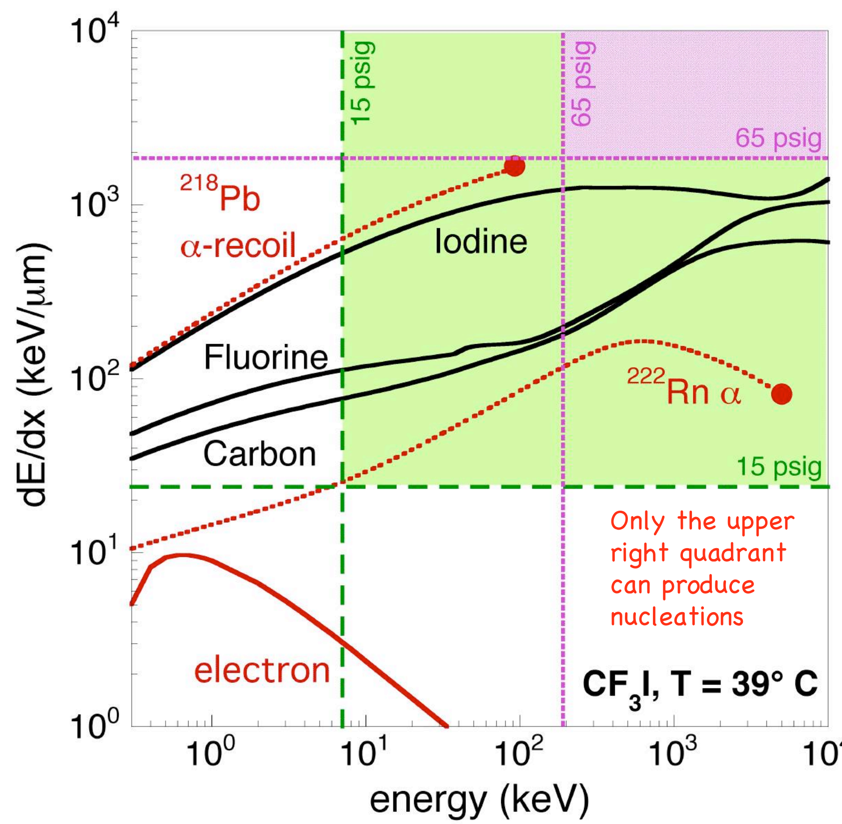
Seitz model of bubble nucleation (classical BC theory):

Threshold in deposited energy

$$E > E_c = 4\pi r_c^2\left(\gamma - T\frac{\partial\gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P \quad , \quad r_c = 2\gamma/\Delta P$$

$$dE/dx > E_c/(a r_c)$$

Threshold also in stopping power, allows for efficient INTRINSIC MIP background rejection



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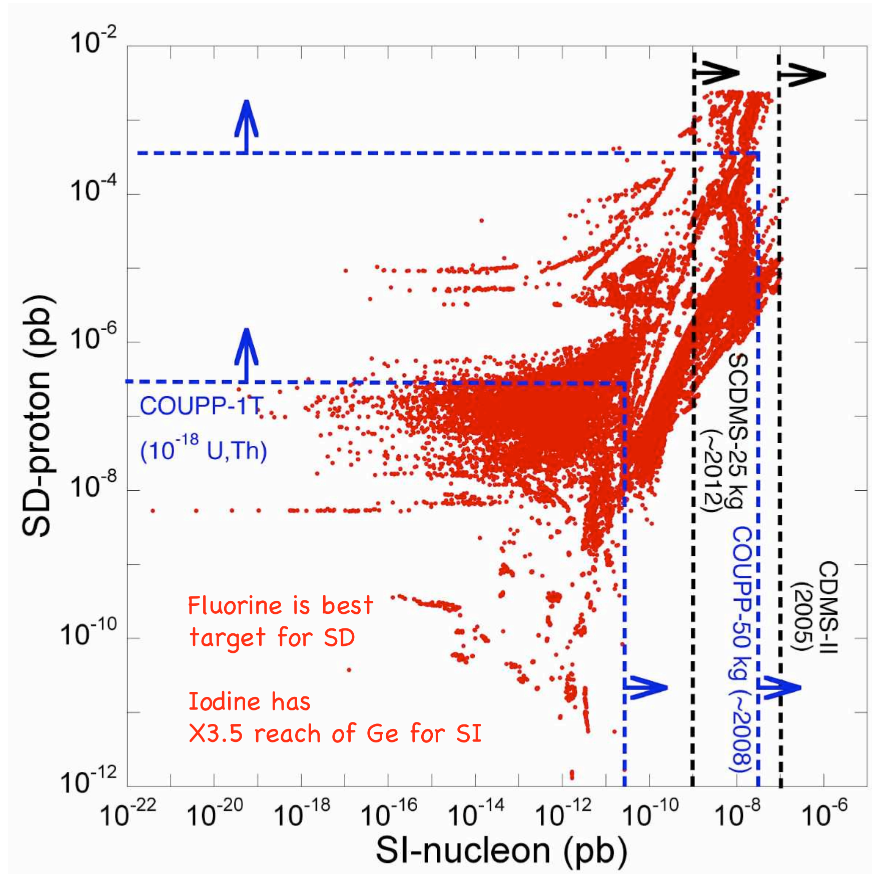
An old precept: attack on both fronts



Baltz & Gondolo, JHEP 0410:052,2004. (WMAP-II update)

SD SUSY space harder to get to, but more robust predictions (astro-ph/0001511, 0509269, and refs. therein)

COUPP approach to WIMP detection:

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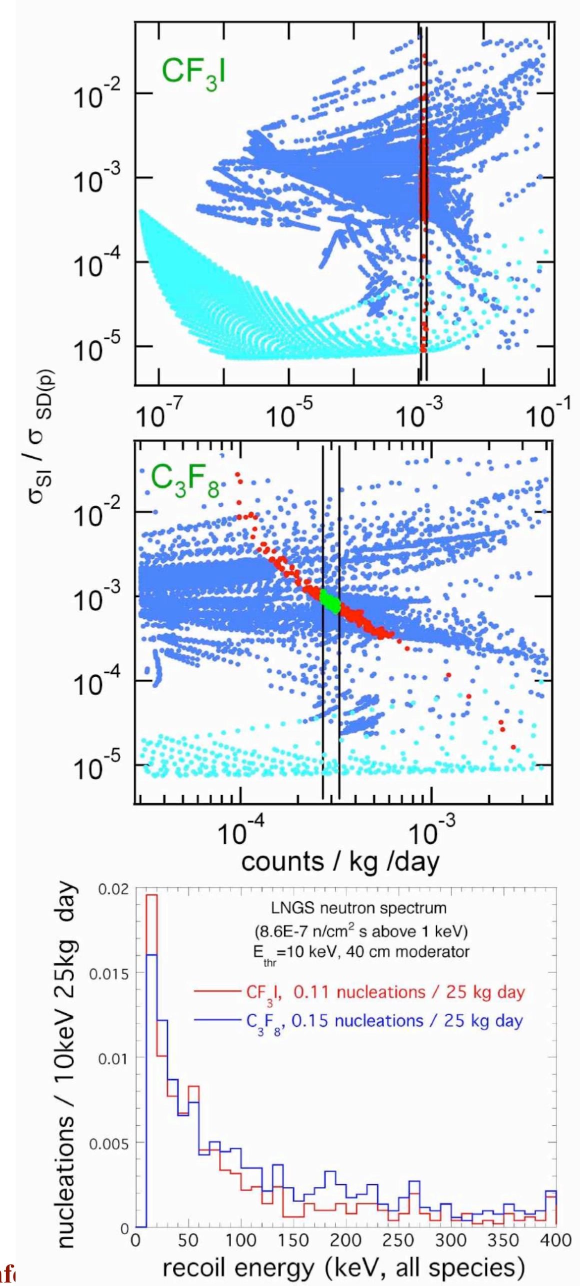

Bertone, Cerdeno, Collar and Odom (in preparation)

Rate measured in CF_3I and C_3F_8 (vertical bands) tightly constrains responsible SUSY parameter space and type of WIMP (LSP vs LKKP)

Neutrons on the other hand produce essentially the same rates in both (σ_n for F and I are very similar)

COUPP approach to WIMP detection:

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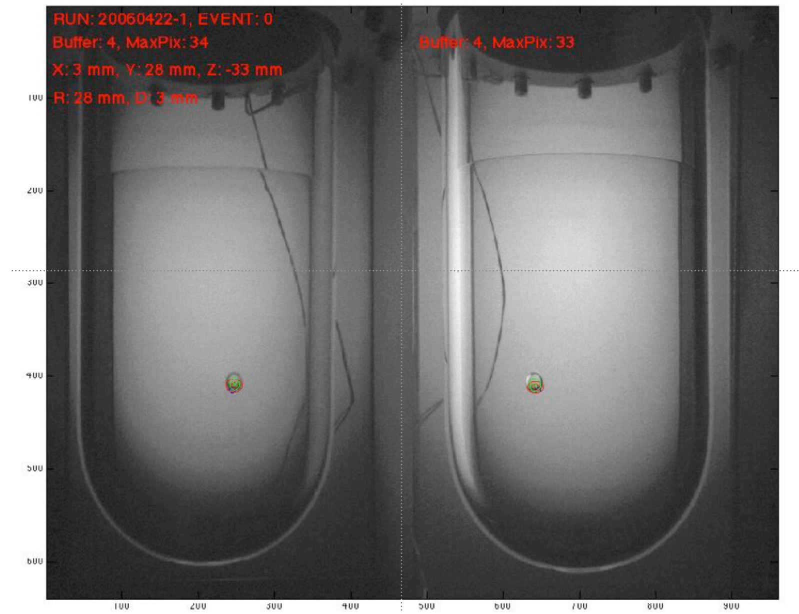
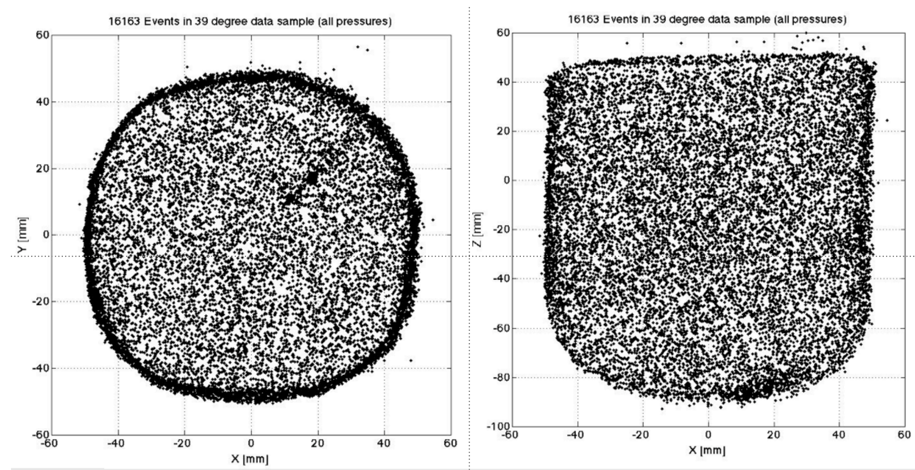
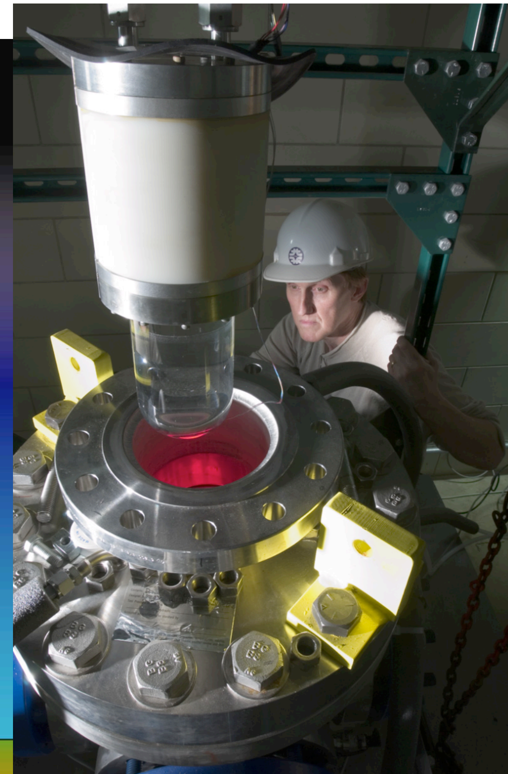
Stereo view of a typical event in 2 kg chamber



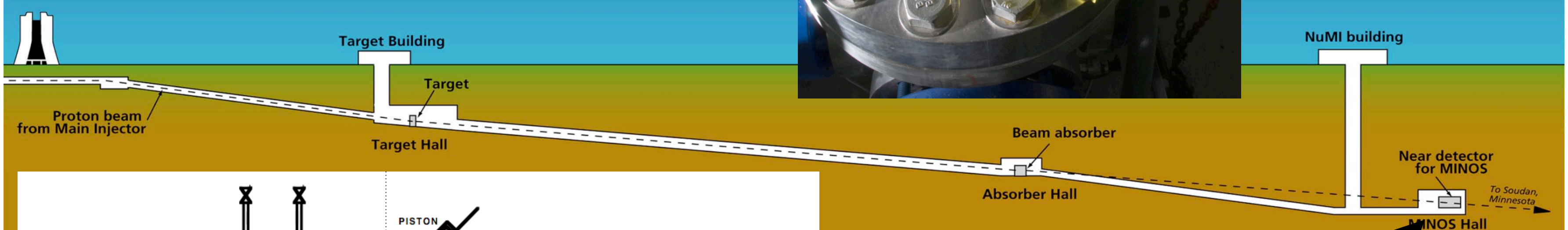


Spatial distribution of bubbles (~1 mm resol.)

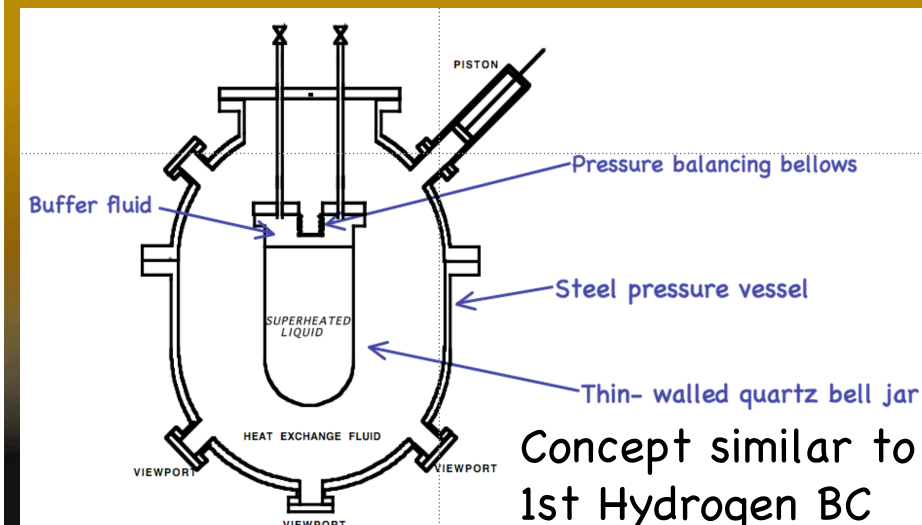
COUPP @ NuMI Tunnel Project (Fermilab Test Beam Proposal T945)



2kg (1l) CF_3I chamber built at UC installed May '05



test site ~300 m.w.e.



Concept similar to 1st Hydrogen BC

Continuous Operation: December '05 to Oct '06

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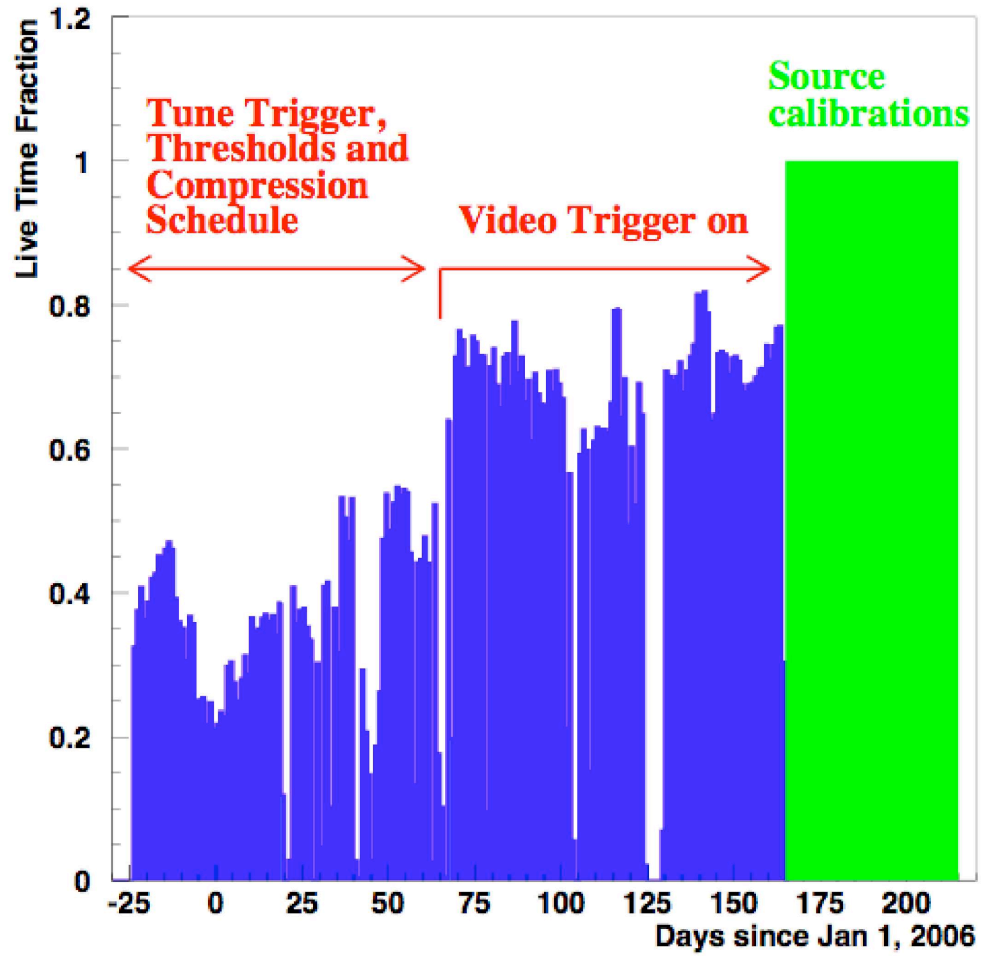
307 days in run
115k expansions
140 seconds mean
superheated time

170 live days
= 55% of calendar time

~70% live time after stabilization

50.8k bubbles counted

324 GB in Enstore

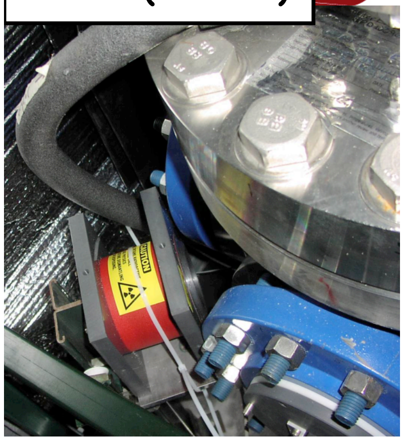


Goals of TBP T945:

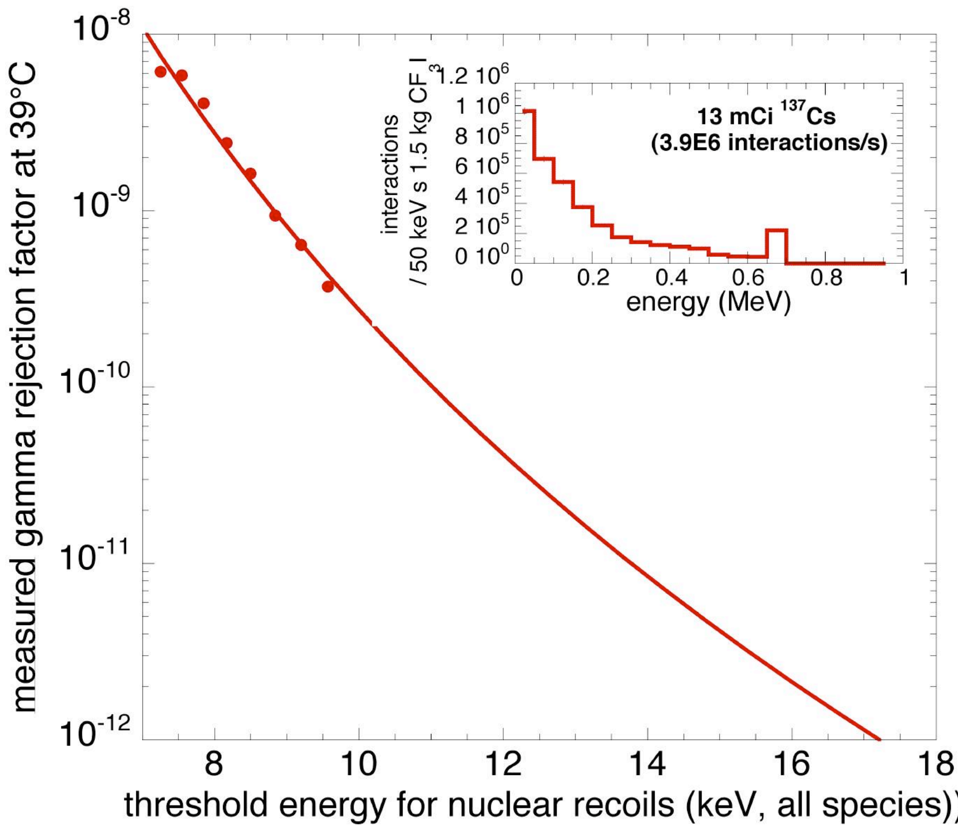
- Demonstrate reliable operation.
- Study backgrounds (they were expected!)
- Calibrate with sources: γ, n.

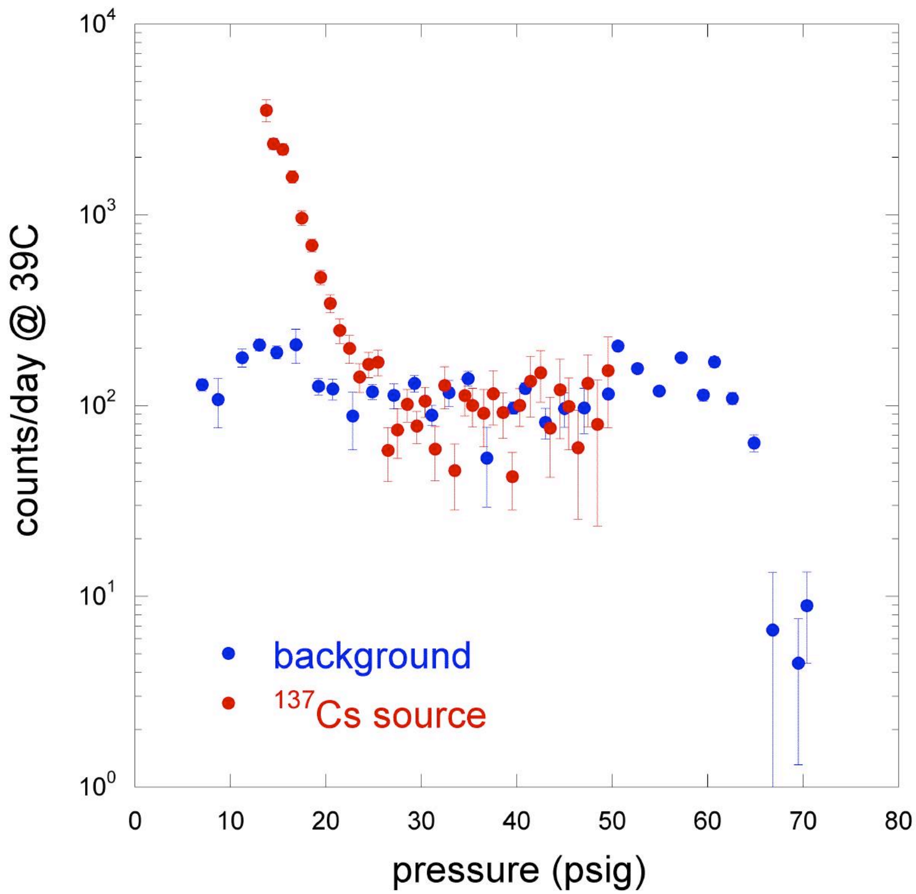
Gamma and neutron calibrations *in situ:*

^{137}Cs (13mCi)



Best MIP rejection factor measured anywhere ($<10^{-10}$ INTRINSIC, no data cuts)





Other experiments as a reference:

XENON ~10^{-2}

CDMS 10^{-4}-10^{-5}

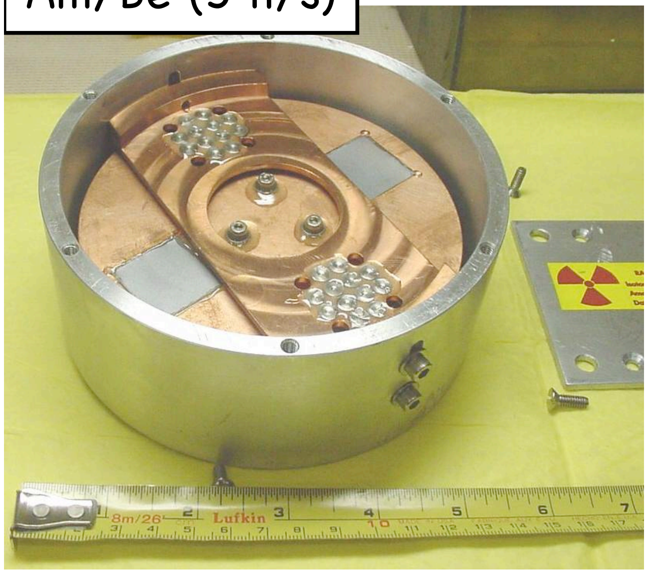
WARP ~10^{-7}-10^{-8}

^{14}C betas not an Issue for COUPP (typical O(100)/kg-day)

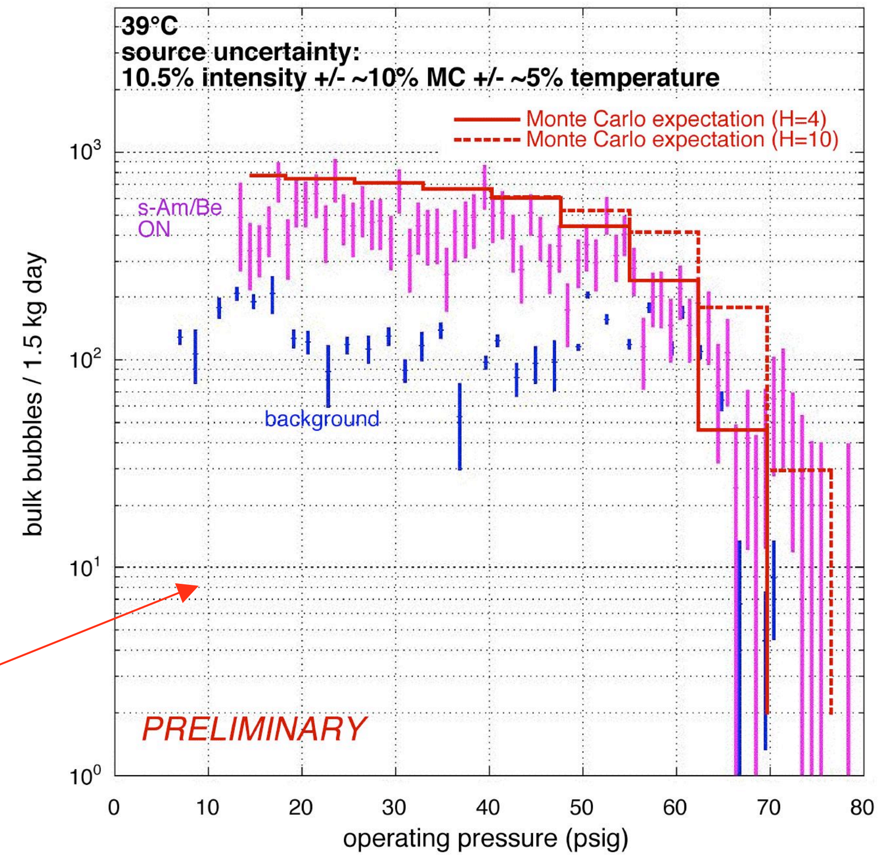
<u>No need for high-Z shield nor attention to chamber material selection</u>

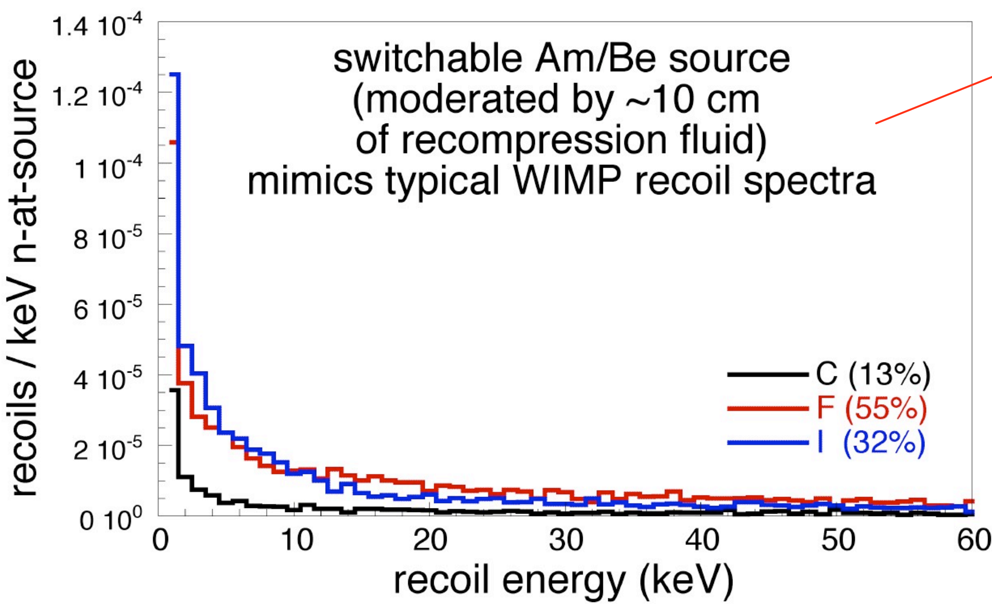
Gamma and neutron calibrations *in situ:*

Switchable Am/Be (5 n/s)



O(0.2) n/day when OFF. Second generation design produces none.





S-Am/Be can be used for ~daily calibration of chamber response (important when searching for DM modulations)

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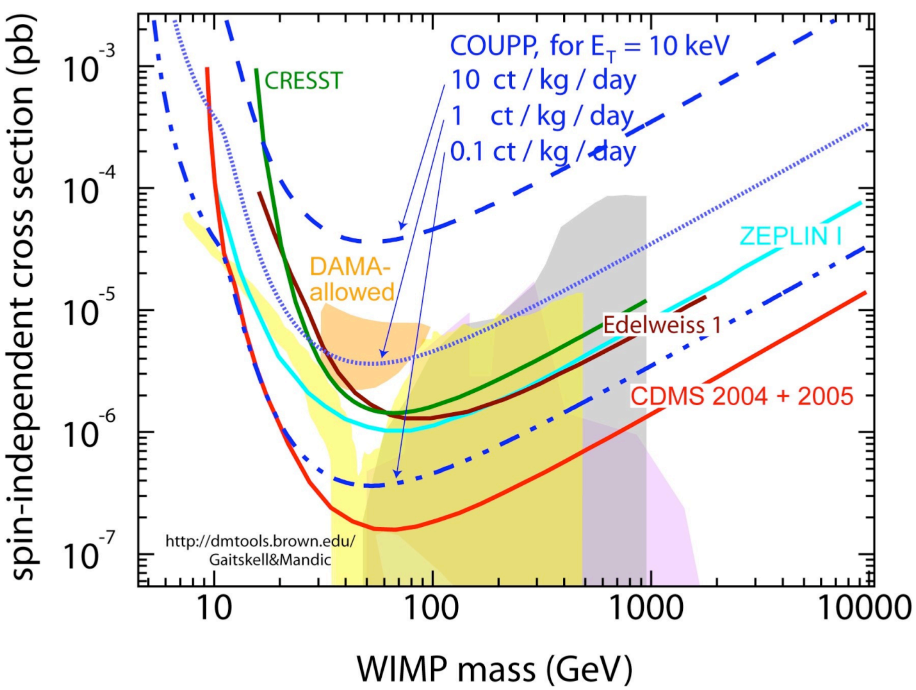
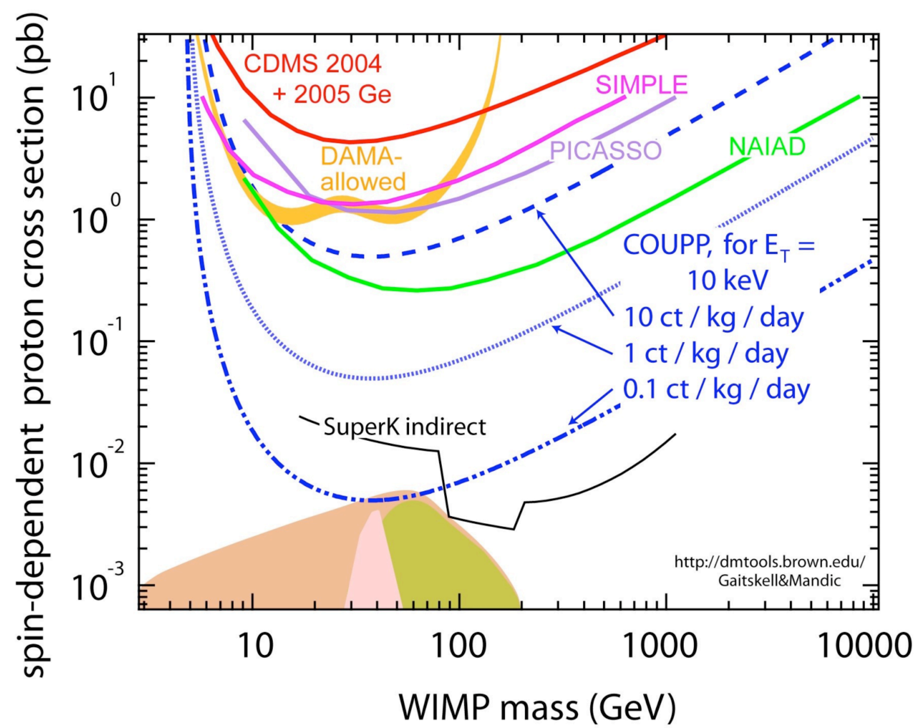
Physics Reach at Fermilab Site

Goal for E-961: reduce background to <<1 event per kg per day

Spin-independent



Spin-dependent

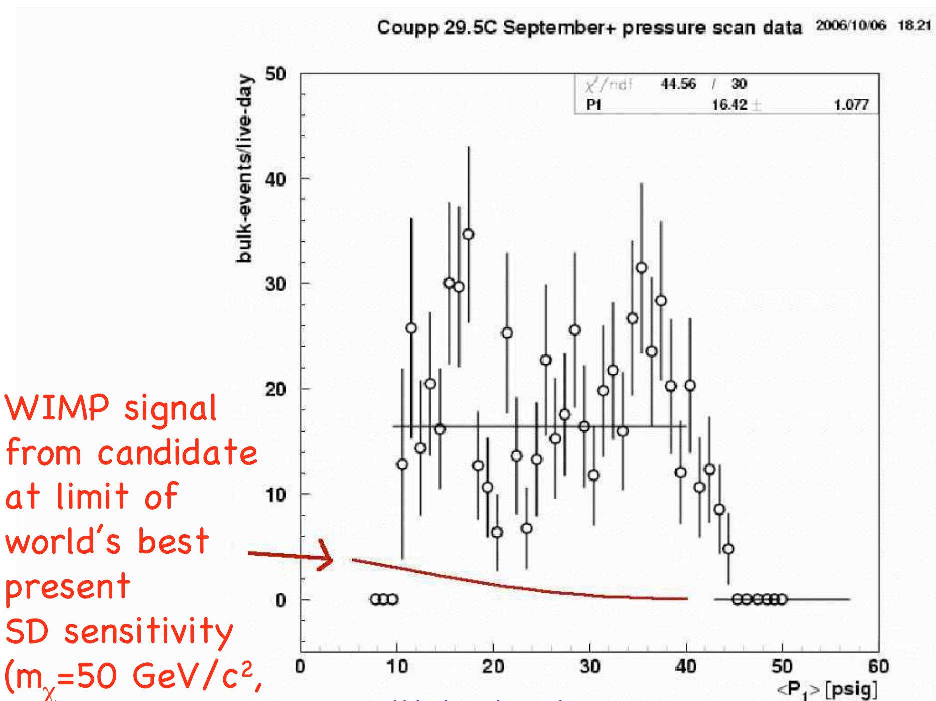


Three projections are offered: ~10c/kg-d can be extracted from present data. ~1c/kg-d expected from simulated (μ,n). ~0.1c/kg-d is for 90% efficient μ veto.
A further reduction to ~0.03 c/kg-d is possible (simulated gallery n's percolate through 30 cm polyethylene shield at that level).
By then better than 10^{-15} U,Th needed (World best is KAMLAND @ ~10^{-18}).

Physics Reach at Fermilab Site

Goal for E-961: reduce background to <<1 event per kg per day

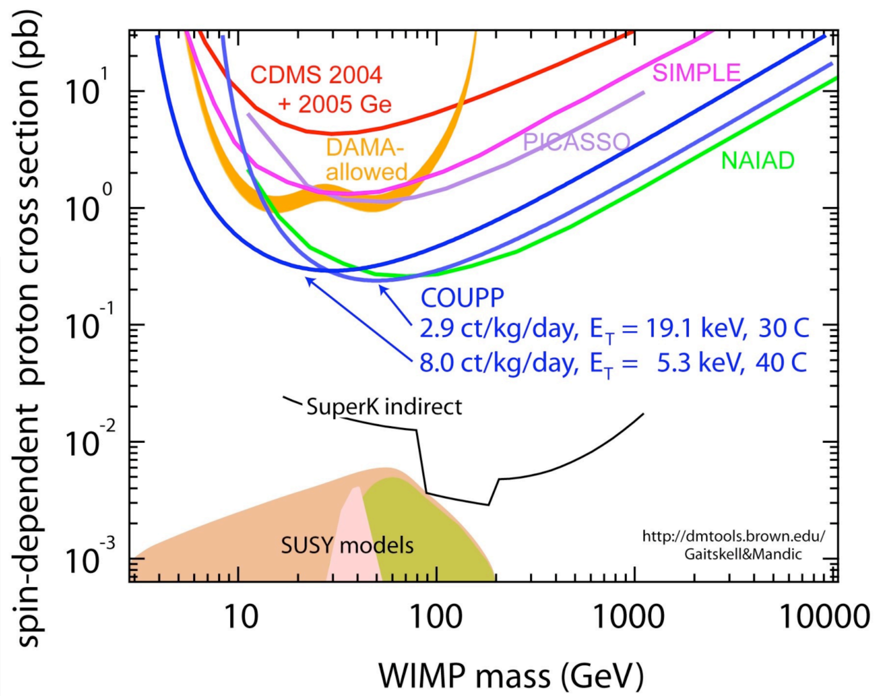
Where exactly are we
in sensitivity as of today?
(next refill should improve it dramatically)



WIMP signal from candidate at limit of world's best present SD sensitivity (m_χ=50 GeV/c², σ_{Wp}= 0.3 pb)

Telltale signature:
Response to α's is flat,
not the case for WIMPs
(or neutrons)

Spin-dependent



<u>Still preliminary</u>
(trying to include systematics,
increase statistics, reduce threshold)

However, even before any Rn mitigation
best SD limits are within reach
(the effect of optimal targets and MIP insensitivity)

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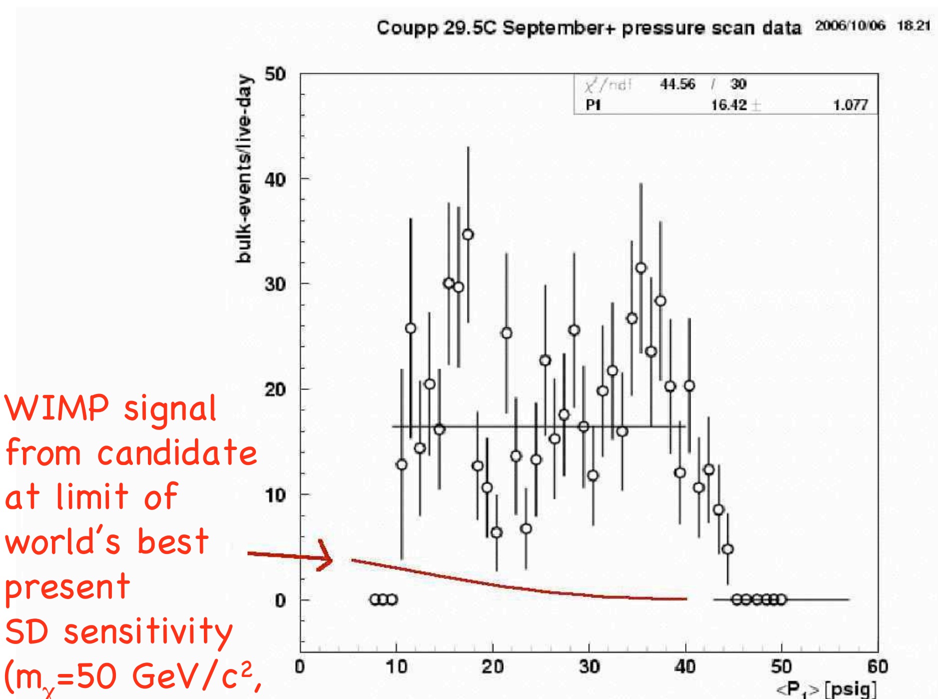

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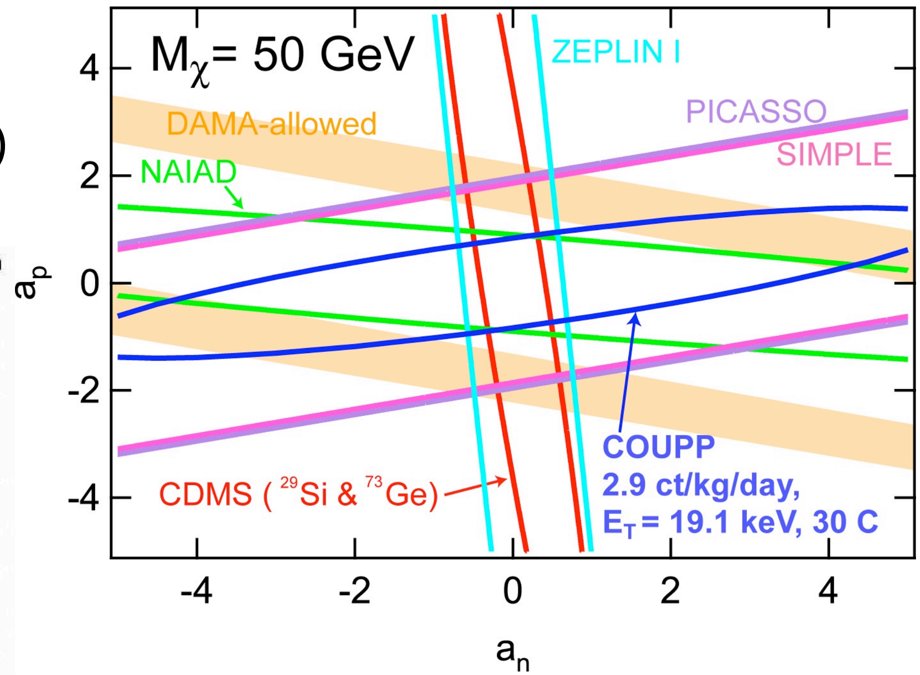

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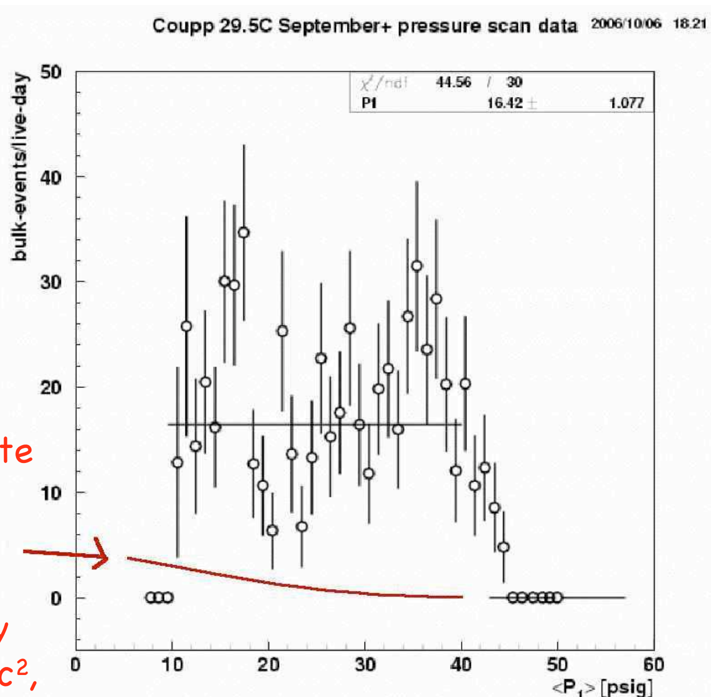

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(m_χ=50 GeV/c^2,
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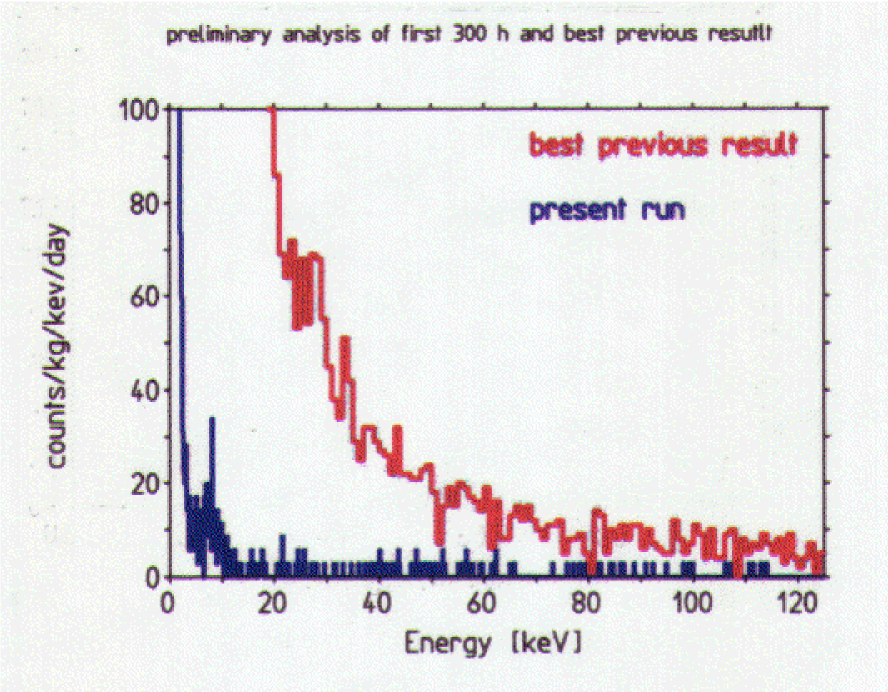
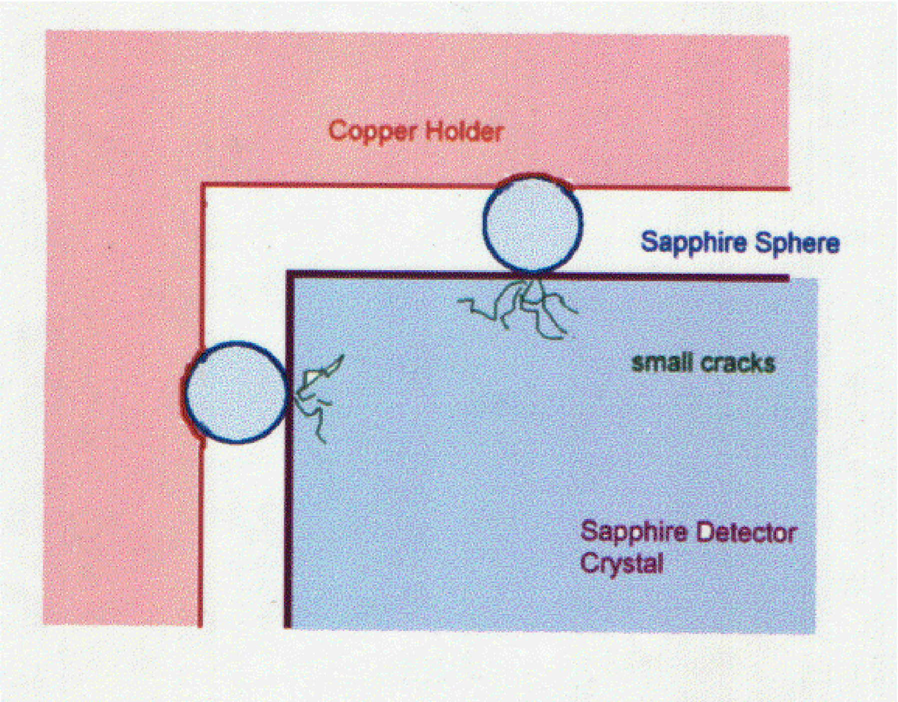
Telltale signature:
Response to α's is flat,
not the case for WIMPs
(or neutrons)

2 chambers (80kg) already
under construction
Official FNAL support
(COUPP = E-961)

Let us be humble for a second (try!)





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Looking for a needle in a stack: a variety of techniques and targets is a must if a compelling case for WIMP discovery is ever to be made

Thanks to E. Aprile, B. Cabrera, R. Gaitskell, C. Galbiati, D. McKinsey and S. Moriyama for updates